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Incorporating transportation safety into land use planning: Pre-assessment of land use conversion effects on severe crashes in urban China

Abstract:

Severe crashes (SCs) have raised significant challenges to public safety in China. Given the prevalence of urban redevelopment, there is an urgent need to incorporate transportation safety into new-phase land use planning. This study presents an approach to pre-assess the traffic safety outcomes of land use conversions by investigating the association between land use conversions and variations in SCs in urban China. Generalized structural equation modelling (GSEM) was used to construct the hierarchical relationships among the SC frequency, land uses, and SC-related features. The Wald test was then employed to examine the reshaping of SC-related features and the SC frequency variation in land use conversions. The results showed that urban residential, commercial and business and mixed residential-commercial land uses had the highest SC risk exposure levels. A set of land use conversions oriented towards these three land uses were positively associated with the SC frequency and would universally drive the reshaping of SC-related features in the traffic volume, accessibility of destinations, and spatial variations in the population and employment at the traffic analysis zone level. These types of conversions were highly sensitive to the generation of mixed traffic flows, thereby leading to a higher risk of exposure to SCs. In contrast, land use conversions were less associated with the reshaping of zonal traffic speeds. The applicability of the proposed approach and the corresponding findings in supporting land use planning strategies for traffic safety improvements in transitional cities and urban China in particular was discussed.

Keywords:

Severe crash; Land use conversion; Transportation safety; China

1. Introduction

Traffic crashes contribute to 1.2 million deaths each year. Globally, this number is growing rapidly due to the increase in motorization and the acceleration of urbanization. Poor road safety has raised significant challenges to public safety, especially in developing countries, where traffic mortality accounts for 90% of the total number of deaths globally (Zhang, et al., 2013). As the country with the highest number of traffic deaths, the situation is particularly severe in China. According to the 2016 report of the Global Burden of Disease project, severe crashes (SCs), including injury and fatal crashes, have become the third leading contributor to premature death in mainland China (Naghavi, et al., 2017). More than 260,000 Chinese people die from road collisions each year. In contrast, in the U.S., a country with a comparable number of registered vehicles, the same figure is a disproportionately low 34,000 (World Health Organization, 2015). Given these alarming figures, there is an urgent need to improve the traffic safety in China.

The ultra-dense population, prevalent vehicle dependency and booming car ownership in urban China have increasingly worsened its traffic safety situation (Zhang, Huang, Roetting, Wang, & Wei, 2006). Additionally, large cities throughout China are experiencing radical changes led by urban redevelopment projects, and the existing built environment and transport system are being widely and purposefully reshaped (Lau, 2013). Given this context, road safety issues might also be subject to unpredictable changes in the absence of effective and targeted countermeasures and strategies. Therefore, transportation safety should be given higher priority in planning practices than ever before.

Development in urban China is inseparable from land use conversion (Liu, Fang, & Li, 2014). Urban land use conversion can be categorized into two modes: urban land use development, defined as a mode in which a non-urban land use within the urban fringe is transformed into an urban land use, and urban land use redevelopment, namely, a mode in which a specific type of urban land use is converted into another within urban internal spaces (Zhou, Li, Li, Zhang, & Liu, 2016). Since the implementation of the reform and opening up policies in the late 1970s, Chinese cities have experienced remarkable growth. Serving as a crucial economic asset, land has played a pivotal role in the accumulation of local capital and in turn contributed to substantial transformations of the built environment and urban expansion (Lin & Yi, 2011). Nevertheless, in recent years, similar to the most transitional countries under rapid urbanization, the deficiency of non-urban land uses in China has catalysed urgent efforts to rein in the expansion of built-up areas and to encourage urban redevelopment within urban internal spaces (Chen, Wang, & Guo, 2016). Given this scenario, urban land use redevelopment, the aim of which is to optimize the existing land structure via the reconfiguration and rearrangement of land parcels, has dominated planning projects and become the mainstream development mode in China's large cities. Consequently, unprecedented opportunities for traffic safety improvements within inner cities have emerged. Hence, new-phase land use conversions should be taken as a central strategy in promoting long-range traffic safety and creating travel-friendly environments in urban China. Correspondingly, assessing the potential safety outcomes prior to the implementation of conversion strategies, namely, performing a pre-assessment, would become particularly important.

As the fundamental landscape component that shapes diversified regional forms and functions, the roles of individual land use classes, including commercial (Kim, Pant, & Yamashita, 2010), industrial (Priyantha Wedagama, Bird, & Metcalfe, 2006), residential (Kim & Yamashita, 2002), educational (Sebos, Progiou, Symeonidis, & Ziomas, 2010), and official land uses (Narayanamoorthy, Paleti, & Bhat, 2013), in explaining SCs have been continually investigated. Several recent studies have also emphasized the effects of land use structures on SCs. Previous studies have found that a mix of land uses is positively associated with the frequency and severity of crashes (Miranda-Moreno, Morency, & El-Geneidy, 2011; Verzosa & Miles, 2016b). Additionally, Pulugurtha, Duddu, and Kotagiri (2013) found that a delicate balance of land use structures may reduce the frequencies of total and fatal crashes. Nevertheless, although these studies provide a basic empirical basis for crafting land use conversion countermeasures against the prevalence of SCs, they are limited in several ways.

First, the literature is replete with studies incorporating land use variables and variables of other SC risk factors into the same non-hierarchical estimation models while simultaneously overlooking the interrelationship, namely, the hierarchical structure, among those factors. Land uses have played a crucial role in shaping crash-related factors, such as the transportation network, accessibility to destinations, and spatial variation in employment and population (Pulugurtha, et al., 2013; Shoshany &

Goldshleger, 2002; Xiao, Sarkar, Webster, Chiaradia, & Lu, 2017); in turn, these factors have implications for the traffic volume and speed, two major determinants of the area-level traffic safety (Ewing & Dumbaugh, 2009; Ewing, Hamidi, & Grace, 2016). To illustrate this situation with an example, the enlargement of commercial areas is accompanied by rises in the zonal employment density, the number of commercial facilities, and the street connectivity; under such circumstances, larger traffic volumes would be produced as origin- and destination-specific trips are eventually generated more frequently, while traffic speeds would be depressed, a result attributable to increased numbers of road conflicts; all of these factors (i.e., employment density, accessibility to commercial facilities, street connectivity, and traffic volumes and speeds) are closely associated with both land uses and SCs. Accordingly, non-hierarchical modelling might lead to an underestimation or overestimation of land use effects on SCs.

In addition, as mentioned above, the essence of land use conversion is the mutual transformation among various types of land uses (Zhou, et al., 2016). To wit, these land uses are always intertwined and associated with others being converted since the area of overall land use remains constant. To date, most studies have not explicitly constructed these transformation relationships in a modelling framework; correspondingly, the variation in SCs and the reshaping of SC-related features in land use conversions, which constitute a key prerequisite for the pre-assessment of conversion strategies, remain to be explored.

As such, the two objectives of the research presented in this paper are as follows:

(1) Explore the hierarchical relationship among land uses, SC-related features, and the SC frequency by employing generalized structural equation modelling (GSEM).

(2) Construct land use conversions and explain the reshaping of SC-related features and variations in the SC frequency in the conversions at the traffic analysis zone (TAZ) level using the Wald test.

2. *Literature review*

2.1. *Mediators for the association between land uses and crashes*

The existing evidence is generally supportive of the belief that traffic volumes and traffic speeds are major determinants of the macro-level (e.g., the community-, TAZ-, and city-level) traffic safety. On the one hand, passive safety theory assumes that driver errors are a function of the accumulation of driving behaviours (Dumbaugh & Li, 2010). A vast repository of literature has associated greater exposure to traffic volume with a higher frequency and a higher severity of SCs (Ewing, et al., 2016; Morency, Gauvin, Plante, Fournier, & Morency, 2012; Verzosa & Miles, 2016a). On the other hand, it is widely accepted that higher traffic speeds shorten the response time to react to instantaneous traffic risks, increase the occurrence of a potential crash, and exacerbate the probability of severe injuries resulting from crashes, *ceteris paribus* (Abdel-Aty, Lee, Siddiqui, & Choi, 2013; Haleem, Alluri, & Gan, 2015; Yu & Abdelaty, 2014).

A systematic review has proposed a conceptual framework to illustrate how two important dimensions of the built environment, namely, development patterns and roadway designs, are associated with traffic safety through traffic volumes and traffic speeds (Ewing & Dumbaugh, 2009). In this framework, traffic volumes and speeds are considered as the primary determinants of the crash frequency and crash severity, respectively. Although both development patterns and roadway designs are associated with traffic volumes and speeds to a certain extent, the primary mechanism by which they affect the traffic safety varies. In general, development patterns, which are reflected by the land use, distribution of sociodemographic components, spatial structure of urban elements, and accessibility to destinations, influence crashes primarily via the traffic volumes they generate. The roadway design, including the type of roads, street connectivity (e.g., characteristics of conflict points), road width, and roadside parking, impacts SCs primarily through the traffic speeds they allow.

Similarly, the research conducted recently by Najaf, Thill, Zhang, and Fields (2018) has examined the relationship between traffic safety and the city-level urban form, which is conceptualized as a physical configuration of the parts constituting a city from the land use pattern and distribution of sociodemographic components of a city to the citywide layout of the transportation network and travel demand. Their research team conceptualized and identified four potential mediators, namely, traffic congestion, non-driving transport modes, walkability, and average commuting time, all of which were deemed to be closely associated with traffic volumes and speeds at the area level.

Prior studies have examined the correlation between crashes (both overall and severe) and their neighbouring land use characteristics; in this correlation, crashes are affected by land uses primarily through the traffic volumes and secondarily through the speeds. The classic four-step model (FSM) provides a mechanism by which traffic volumes are evaluated, calibrated, and validated during four sequential processes, namely, trip generation, trip distribution, mode split and network assignment, based on the land uses (Zhong, Shan, Du, & Lu, 2015). As the integral reflection of zonal functions, land uses play a vital role in shaping both the destination accessibility (Wee, 2011) and the spatial variation in the employment and population (Lu & Guldmann, 2015; Shoshany & Goldshleger, 2002) and hence the generation of human activities (e.g., economic and travel activities). In the FSM, the activity system, which is characterized by the land uses and the activities that occur in those land uses, determines the initial trip productions, trip attractions, and travel demand (Pulugurtha, et al., 2013).Through the transportation system, another factor associated with land use characteristics, an equilibrated network traffic flow is then created (Mcnally, 2000). In addition, traffic speeds are associated with land uses to a certain extent. In dense urban areas (e.g., residential and commercial zones) and institutional areas, enhanced traffic-calming measures would largely reduce traffic speeds and improve the traffic safety performance (Ewing & Dumbaugh, 2009). Moreover, these areas are also associated with more intersections, a result attributable to a higher street network connectivity (Xiao, et al., 2017), ultimately contributing to lower-than-prevailing traffic speeds (Guevara, Washington, & Oh, 2004).

2.2. *Crash-related factors*

Land use characteristics has been examined in numerous investigations on crashes. The literature has largely found that the proportions of commercial and business land uses are positively associated with the SC frequency (Wier, Weintraub, Humphreys, Seto, & Bhatia, 2009). Moudon, Lin, Jiao, Hurvitz, and Reeves (2011) found that large commercial centres increase the probability of fatalities in pedestrian collisions. Dumbaugh and Li (2010) differentiated commercial land uses in terms of their morphology and spatial configuration and observed that commercial strip land may increase all types of crashes, while few crashes occur in areas with pedestrian-scale retail uses. Regarding residential land use, Pulugurtha, et al. (2013) reported that areas with higher-density residential (urban residential) land uses present a positive correlation with fatal crashes. Moreover, SCs occur more frequently in TAZs with larger areas devoted to resources and industrial land uses (Hadayeghi, Shalaby, & Persaud, 2010), although these areas are closely associated with fewer pedestrian collisions (Chen & Zhou, 2016). Lee, Yasmin, Eluru, Abdelaty, and Cai (2017) also indicated that land uses that are remote from urban areas are associated with a higher proportion of light truck-involved crashes. In contrast, as a particularly unfriendly and inaccessible zone, military land use inhibits SCs to a certain extent (Kim, et al., 2010). Scholars have also found that governmental (Hadayeghi, et al., 2010) and office land uses (Narayanamoorthy, et al., 2013) might be positively correlated with the frequency of crashes, whereas open and green spaces could decrease the crash occurrence (Miranda-Moreno, et al., 2011). In addition, several previous studies considered different land use structures and found that highly mixed land uses could have positive implications on the frequency of crashes (Verzosa & Miles, 2016a) and exacerbate the crash severity (Mohamed, Saunier, Miranda-Moreno, & Ukkusuri, 2013). Furthermore, Wang, Yang, Lee, Ji, and You (2016) observed that pedestrian crashes may increase with an increasing development intensity.

A plethora of studies have found significant correlations between SCs and sociodemographic characteristics. For different demographic groups, children and older adults are more vulnerable to SCs in particular (Aguero-Valverde & Jovanis, 2006; Wier, et al., 2009). More pedestrian crashes might also occur in areas with a higher proportion of African Americans (Jaeyoung, Mohamed, & Ximiao, 2015). Aguero-Valverde and Jovanis (2006) found that greater numbers of SCs are observed in areas with larger proportions of an impoverished population. Similarly, Noland and Quddus (2004) observed that area-level multiple deprivation can have positive implications for traffic casualties. Lee, Abdel-Aty, and Choi (2014) also found that the median family income presents a positive correlation with the number of at-fault drivers within ZIP codes. In contrast, a lower proportion of households without an available vehicle within a ZIP code is negatively associated with the risk for pedestrians to be involved in a crash (Lee, Abdelaty, Choi, & Huang, 2015).

Researchers have also focused on the role of the transportation network in crashes.

For example, increases in the road mileage and road density are associated with a higher SC frequency (Aguero-Valverde, 2013; Aguero-Valverde & Jovanis, 2006). Hadayeghi, et al. (2010) reported that the lengths of arterial roads, collector roads and laneways constitute a positive predictor for the SC frequency. Moreover, additional pedestrian- and bicycle-involved crashes occur in areas with a higher proportion of local roads (Cai, Lee, Eluru, & Abdel-Aty, 2016). Lengths of roadways with poor pavement are also positively correlated with the SC frequency (Lee, Abdel-Aty, & Jiang, 2014). A higher proportion of arterial streets without public transit also tends to increase the injury crash occurrence (Wier, et al., 2009). A county-level study found that more SCs occur in areas with a higher density of principal arterial roads and minor arterial roads; in contrast, the density of freeways is negatively associated with the SC frequency (Huang, Abdel-Aty, & Darwiche, 2010). Meanwhile, the existing findings on intersections are inconsistent. Ukkusuri, Miranda-Moreno, Ramadurai, and Isa-Tavarez (2012) found that the density of complicated intersections is positively correlated with the pedestrian-involved SC frequency, as intersections are regarded as conflicts between pedestrians and vehicles. In contrast, several researchers indicated that intersections, especially simple 3-way types, are negatively associated with the crash frequency, which might be attributed to the lower traffic speeds in those intersections (Cai, et al., 2016; Dumbaugh & Li, 2010; Guevara, et al., 2004).

Another set of studies recently examined the relationship between SCs and the destination accessibility. Destinations are expected to attract a larger traffic volume and more human activity within their vicinity than their adjacent regions (Jiao, Moudon, & Li, 2013). Accordingly, the density of bus stops has been found to be positively correlated with the frequency of SCs (Kim, et al., 2010), and SCs are also more likely to take place near schools for pedestrians and cyclists (Zahabi, Strauss, Manaugh, & Miranda-Moreno, 2011). Moreover, several scholars have noted that commercial and institutional facilities, such as retail stores (Lee & Abdelaty, 2017), big box stores (Dumbaugh & Li, 2010) and neighbourhood commercial centres (Moudon, et al., 2011), might have a bearing on the frequency and severity of crashes. Additionally, Jiao, et al. (2013) noted that destination proxies must be carefully selected and utilized. For example, the density may embody the effects of bus stops on pedestrian collisions more robustly than a presence proxy.

As such, a framework is proposed in this paper to explore the potential mechanism by which variations in the SC frequency are affected by land use conversions (**Figure 1**). In this framework, land use conversions reshape the spatial variations in the employment and population, layout of the transportation network, and destination accessibility. We hypothesized that along with the mediating effects of the traffic volumes and speeds, these changes ultimately result in variations in the SC frequency at the TAZ level.

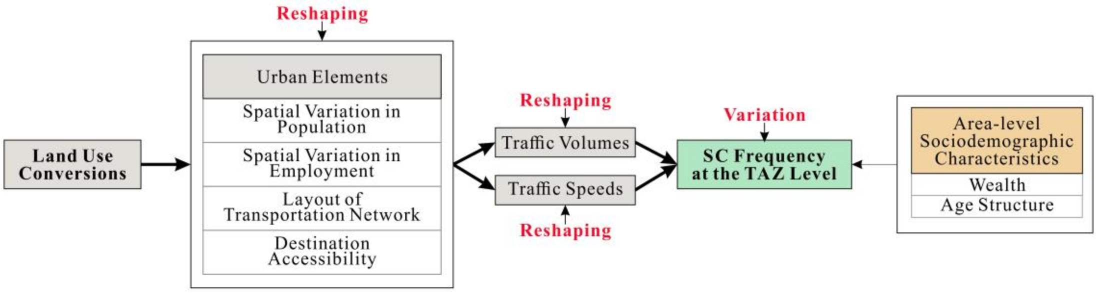


Figure 1 Potential linkage between land use conversions and variations in SCs at the TAZ level.

3. *Research design*

3.1. Study area and data sources

The city centre of Wuhan served as the study area. In 2015, 70.12% of all SCs in Wuhan occurred in this focal area (**Figure 2**). As the largest metropolis in central China, Wuhan is growing rapidly coincident with high-speed urbanization, which has increased vehicle ownership considerably, especially over the last decade. According to the 2016 Wuhan Vehicle Emission Control Annual Report, this figure has increased continually by an annual rate of over 10% since 2011 (Wuhan Environmental Protection Bureau, 2017). In addition, more than 60% of all residents of Wuhan are concentrated in the centre of the city with a gross population density of 8,771 people per km^2. To maintain economic development therein and meet the surging residential requirements, residential, commercial and mixed residential-commercial land uses have dominated the land use planning in this area. As a result, larger and more mixed traffic flows, which could exacerbate the risk of exposure of residents in our focal area to both pedestrian-involved and vehicle-to-vehicle SCs, have been generated throughout the city centre.

For the basic research units, the TAZs (n=602) were adopted. Two types of data were used in this study: SC records and environmental features. In the current study, SCs were defined as crashes that involved the first harmful event and resulted in a fatality or an incapacitating injury. SC data from 2015 were extracted and provided by Wuhan Emergency Medical Centre (WEMMC), which is responsible for receiving and collecting information on all crashes involving the first harmful event from the Wuhan Public Security Bureau and sending the injured to the suitable hospital according to the severity. Environmental data, including land use, traffic volume, traffic speed, population, employment, point of interest and road network data, from 2015 were derived from the Wuhan Land Resources and Planning Information Centre. The SC records and environmental features in each TAZ were geocoded and quantified by using the ArcGIS overlay and spatial join functions. The descriptive statistics and descriptions of the variables considered and included in this study are shown in **Table 1**.

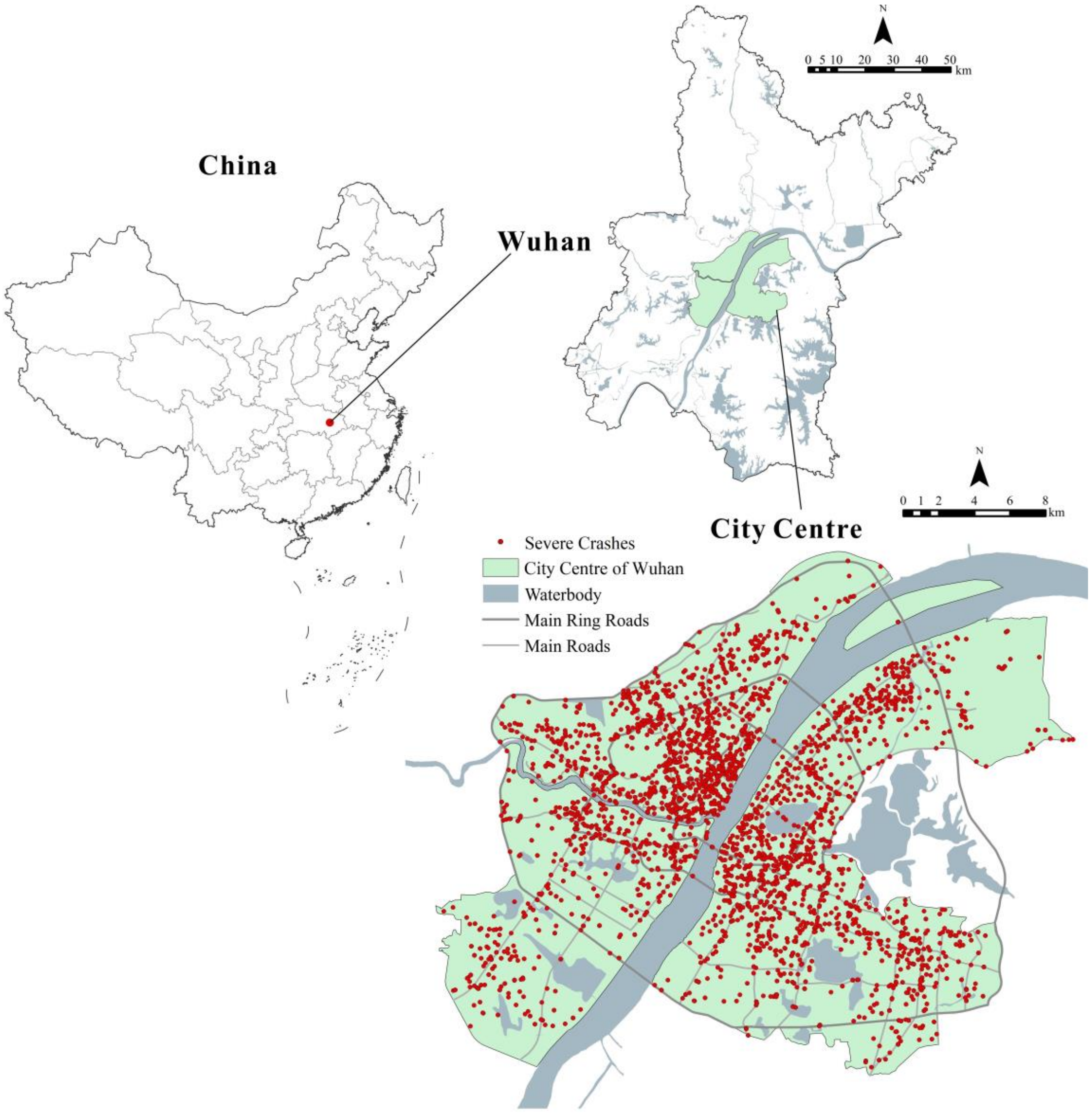


Figure 2 SC locations in Wuhan, China (2015).

Table 1 Summary and definition of variables.

Domains	Variables	Mean	SD	Min	Max	Description
Severe Crash	Severe Crash Frequency	10.31	10.55	0.00	70.00	Number of severe crashes occurring in a TAZ (n).
Land Use Pattern	Land Area	75.20	81.13	3.49	1565.71	Total land area of TAZ (ha).
	Urban Residential (UR)	18.94	18.64	0.00	113.53	Area of urban residential district, including areas with 3-grade residential uses and neighbouring service facilities (ha).
	Government & Office (G&O)	2.79	4.70	0.00	37.84	Area of governmental and office district, including areas with education, health care and social welfare uses (ha).
	Commercial & Business (C&B)	10.60	18.25	0.00	180.13	Area of commercial and business district, including areas with retail, commercial, recreation, business, and culture uses (ha).
	Mixed Residential-Commercial (MRC)	0.13	0.74	0.00	13.17	Area of mixed residential and commercial district, which is typically associated with high-intensity development (ha).
	Public Space (PS)	3.45	9.45	0.00	111.34	Area of green and public district (ha).
	Industrial (IND)	12.54	50.54	0.00	1104.92	Area of industrial district, including areas with research and manufacturing uses (ha).
	Transportation (TRANS)	6.02	10.46	0.00	114.28	Area of transportation land use, including areas with railway, highway, urban road and neighbourhood pathway uses (ha).
	Infrastructure (INFRA)	1.76	5.34	0.00	83.30	Area of infrastructure land use, including areas with safety and basic provision uses (ha).
	Warehouse (WHSE)	1.40	4.47	0.00	52.68	Area of warehouse land use (ha).
	Area under Construction (AUC)	7.06	12.10	0.00	126.94	Area of district under construction (ha).
	Village Construction (VC)	10.50	28.65	0.00	402.50	Area of village settlement district (ha).
Traffic Volume	Vehicle Miles Travelled (VMT)	11.04	1.98	6.36	13.02	Annual average daily traffic multiplied by the length of the road segment (this variable was transformed by the natural logarithm).
Traffic Speed	Road Speed < 25 KPH	0.06	0.15	0.00	1.00	Proportion of roads with an average driving speed below 25 KPH (%).
	Road Speed between 25 and 35 KPH	0.20	0.24	0.00	1.00	Proportion of roads with an average driving speed between 25 and 35 KPH (%).

	Road Speed between 35 and 45 KPH	0.21	0.25	0.00	1.00	Proportion of roads with an average driving speed between 35 and 45 KPH (%).
	Road Speed > 45 KPH	0.13	0.21	0.00	1.00	Proportion of roads with an average driving speed over 45 KPH (%).
Spatial Variation in Population	Population Density	17.25	19.24	0.00	119.14	Population/ land area of the TAZ (k/ha).
Spatial Variation in Employment	Employment Density	7.58	6.18	0.00	36.22	Employment population/land area of the TAZ (k/ha).
Layout of Transportation Network	Major Road Density	0.09	0.06	0.03	0.33	Major Road length/ land area of TAZ (km/ha).
	3-way Intersection	12.47	29.29	27.00	467.00	Number of 3-way intersections (n).
	4-way Intersection	7.09	9.95	13.00	111.00	Number of 4-way intersections (n).
	5-or-more-way Intersection	0.80	1.92	0.00	25.00	Number of 5-or-more-way intersections (n).
Destination Accessibility	*Corporation Density*	3.60	5.16	0.00	38.45	Number of corporations/land area of the TAZ (1/ha).
	Car park Density	0.09	0.11	0.00	0.88	Number of car parks/land area of the TAZ (1/ha).
	Catering Service Density	0.63	0.92	0.00	7.61	Number of caterings/land area of the TAZ (1/ha).
	Metro Station Density	0.02	0.05	0.00	0.42	Number of metro stations/land area of the TAZ (1/ha).
	Bus Stop Density	0.06	0.05	0.00	0.32	Number of bus Stops/land area of the TAZ (1/ha).
	Number of Parks	2.05	9.39	0.00	66.00	Number of parks of the TAZ (1/ha).
Age structure	*Children*	0.05	0.02	0.00	0.12	Population aged under 12/census population (%).
	Adolescents	0.03	0.01	0.00	0.09	Population aged between 12-18/TAZ population (%).
	Adults	0.72	0.09	0.00	0.89	Population aged between 19-59/TAZ population (%).
	Older Adults	0.18	0.05	0.00	0.30	Population aged above 60/census population (%).
Household Wealth	Housing Price	10922.31	2245.02	3681.08	25996.00	Average housing price of the TAZ. (yuan)

Note: items in italics denote variables considered but not included in the research.

3.2. Examination of spatial dependency

Previous research has suggested that the spatial dependency of dependent variables might lead to endogeneity issues in area-level estimations and ultimately contribute to biased results (Lesage & Pace, 2009). Accordingly, before the implementation of the statistical analyses, the global Moran's I statistic was calculated to measure the spatial autocorrelation of the SC frequency within the TAZs across the whole focal area. Global Moran's I values closer to 1 or -1 indicate that the SC frequency within a TAZ presents a highly positive or negative correlation, respectively, with the SC frequencies in their adjacent TAZs. Regarding our dataset, the global Moran's I was calculated to be 0.037 (p-value<0.01), indicating that the SC frequencies within the TAZs are roughly not spatially correlated with other SCs in adjacent TAZs, which might be attributed to the division criteria of TAZs maintaining the homogeneity and uniqueness within TAZs (Pulugurtha, et al., 2013).

3.3. Statistical analyses

3.3.1. GSEM

GSEM was employed to construct the hierarchical relationships among land uses, SC-related features, and the SC frequency at the TAZ level. Compared with univariate and multivariate regression techniques, SEM provides an efficient way to model and examine the interrelationships among structured variables, and it is relatively robust against the potential multicollinearity issue (Malhotra, Peterson, & Kleiser, 1999; Najaf, et al., 2018). Nevertheless, classic SEM is also limited in the modelling of non-linear relationships (Najaf, et al., 2018). Alternatively, GSEM is a flexible generalization of SEM that allows the modelling of response variables with multiple distributions. Previous studies performing research on traffic safety have tended to employ non-linear approaches, such as the Poisson (Lord, Washington, & Ivan, 2005) and negative binomial (NB) models (Zou, Wu, & Lord, 2015), since crash data constitute a non-negative integer variable. The NB distribution, also called the Poisson-Gamma distribution, assumes that the variance should be greater than the mean value, which is consistent with the modelling of dispersed and sporadic crash data (Wei & Lovegrove, 2013). The ability to handle over-dispersion problems makes the NB model efficient in the analysis of crash data, and thus, it has been widely used. More than 12% of all TAZs in our focal area did not report SCs; therefore, GSEM is introduced given the distribution and the nature (i.e., count variable) of SC data. Specifically, the dependent and independent variables were modelled via two types of models and specific canonical link functions: (1) linear models with identity links for continuous dependent variables following a normal distribution; and (2) NB models with logarithmic links for count-dependent variables following a NB distribution (i.e., the SC frequency). The dispersion parameter and likelihood-ratio (LR) test were employed to validate the NB models. The resulting index values significantly greater than zero indicates that the SC data exhibit over-dispersion, and hence, the NB models are preferable to the Poisson model for data modelling herein.

In this analysis, the selected land use variables are included in the GSEM, and all variables are connected to the SC-related features and SC frequency via pathways. Specifically, only the variable of village construction was excluded, while the other 10 land use variables and the total land area variable were included in the GSEM. The objective was to construct village construction-involved land use conversions and examine the variations in the SC frequency and the reshaping of SC-related features during this process. In a multi-variable explanatory model, the corresponding coefficients are used to measure the *ceteris paribus* effect (i.e., the so-called partial effect) of certain land use classes on SCs (Barreto & Howland, 2006). To interpret certain land use effects, only the variables (e.g., the total land area and areas for specific land uses) included in the model should be held fixed, while all other excluded variables should not be subject to an explicit control. Since only the excluded land use variable, i.e., village construction, was not subject to a control, changes in a certain land use area as well as its effect on the SC frequency could only be logical under the premise that the area of village construction changed in the area. Therefore, the setting of these land use variables depicts a set of one-to-one village construction-involved land use conversion relationships.

Eq. (1) shows a specific example of the NB model in the GSEM, in which the village construction variable was excluded from the model. As shown in **Eq. (2)**, when holding the other land use variables fixed (i.e., the total land area A and the area for a specific land use x), a one-unit change in the industrial land use (i.e., IND) would cause the average natural logarithm of the SC frequency (i.e., $log(\theta_i)$) change in γ. Thus, a conversion relationship is constructed between the village construction land use and industrial land use. Likewise, this treatment is also used to examine the relationship between village construction-involved land use conversions and the reshaping of SC-related features.

$$\log(\theta_i) = \alpha_0 + \omega A_i + \gamma IND_i + \beta_j x_{ij} + \varepsilon_i \qquad (1)$$

$$\frac{dlog(\theta)}{dIND} = \gamma \qquad (2)$$

Given the richness of other predictors that we initially considered in the model, several criteria were employed for the selection of other predictors and the construction of pathways. First, severe multicollinearity should not exist among the variables, and classic variance inflation factors (VIFs; best if below 5) were employed to determine the input variables. Moreover, to ensure the fitness and interpretability of the model, the included variables should be either directly or indirectly associated with the SC frequency; thus, the pathways along which the estimated coefficients were not significant at the 0.10 level were ultimately excluded. Before implementing the GSEM, all explanatory variables were normalized.

In addition, the assessment of model goodness of fit was implemented based on three classic indices: (1) comparative fit index (CFI; >0.90) (Hu & Bentler, 1999); (2) goodness of fit index (GFI; >0.90) (Kelloway, 1998); and (3) root mean square error of approximation (RMSEA; <0.08) (MacCallum, Browne, & Sugawara, 1996). As mentioned above, it was *necessary* to retain all the paths (even if they were not significant) between the land use variables and variables of SC-related features/SC frequency in the GSEM in order to construct the conversion relationships. Although this treatment was less associated with the identification of SC-related features, it would largely reduce the model goodness of fit. In order to validate the robustness of identification of SC-related features and the reliability of hierarchical structure, a total of three models were assessed: (1) the main model (i.e., the model we ultimately established); (2) the model that excluded insignificant pathways between land use variables and variables of SC-related features/SC frequency; and (3) the model that excluded land use variables.

3.3.2. Wald test

In **Section 3.3.1**, the treatment and setting of land use variables in GSEM are introduced to illustrate how a set of village construction-involved land use conversions is constructed. Here, by examining the statistical differences (i.e., significant differences) in the total effects of various types of land uses, the Wald test is employed to extend these conversions to broader mutual conversions involving the overall 11 types of land uses and hence examine the reshaping of the SC-related features and variations in the SC frequency in those land use conversions. The logic behind this approach is that the total effects of a certain land use in the GSEM established herein on the SC-related features or SC frequency could be interpreted as changes in the SC-related features/SC frequency in the mutual conversions between that type of land use and village construction. Under such a circumstance, the village construction could be regarded as a reference; furthermore, if the difference between the total effects of two different land uses is statistically significant, the mutual conversion between these two land uses could also contribute to either the reshaping of the SC-related features/variations in the SC frequency.

The Wald test is widely used in tests of hypotheses on parameters based on the Chi-square statistic. As such, to examine the statistical differences between the total effects of different land uses on certain SC-related features/SC frequencies, two hypotheses are constructed as follows:

$$H_0\text{:}\;\; E_1 = E_2 \tag{3}$$

$$H_1\text{:}\;\; E_1 \neq E_2 \tag{4}$$

where H_0 and H_1 are the null hypothesis and the alternative hypothesis, respectively, and E_1 and E_2 indicate the total effects of land use 1 and land use 2, respectively, on certain SC-related features/SC frequencies. The total effect of a certain land use variable on the SC-related features/SC frequency is calculated based on the cumulative impact over all of the involved pathways. If there is a significant difference between E_1 and E_2, their magnitudes could be used to indicate the directions of changes in the dependent variables (i.e., the SC frequency or SC-related features) in this conversion.

4. Results and discussion

4.1. Identification of SC-related features

Using GSEM, hierarchical relationships were established among land uses, SC-related features, and the SC frequency at the TAZ level. Accordingly, the features that were either directly or indirectly associated with the SC frequency were able to be identified. As shown in **Figure 3**, a simplified path diagram was constructed due to the richness of land use variables (total 11 variables) and the related pathways in the GSEM. Specifically, the unidirectional arrows indicate the causal pathway between dependent and independent variables at different levels. The causal pathways of effects estimated based on the NB models are represented by red arrows, and those of effects estimated based on the linear models are represented by blue arrows. The dispersion parameter was calculated to be 1.24 (LR test: p-value<0.001), indicating that the NB model is preferable to the Poisson model in modelling the SC data in our research. To establish the village construction-involved land use conversions, we retained every pathway linking the land use variables and SC-related features/SC frequency. Accordingly, the 'land use' variables represent all land use variables included in the GSEM, and all pathways involved with these variables are depicted by single unidirectional arrows to ensure the readability and clarity of the path diagram. The goodness of fit for models was reported in **Table 2**. The main model presents a relatively poor goodness of fit, which was largely attributed to the insignificant paths between land use variables and variables of SC-related features/SC frequency. Nevertheless, the goodness of fit measures for the model that excluded insignificantly land-use-involved pathways fell in a very good range of GFI and an acceptable range of CFI (>0.8, see Najaf, et al. (2018)), and all the three measures (i.e., CFI, GFI, and RMSEA) for the model that excluded land use variables fell in a very good range, indicating a high robustness of the identification of SC-related feature and a high reliability of the hierarchical structure we established to a certain extent.

We first consider the direct relationships between the SC frequency and selected features (**Table 3**). Many studies have found that traffic volumes are positively correlated with the frequency of SCs (Abdel-Aty, et al., 2013; Dumbaugh & Li, 2010), and this study is no exception. Moreover, our results indicated that a greater exposure to SCs was also expected in TAZs with a larger proportion of medium-speed roads (road speeds between 25 and 35 KPH), *ceteris paribus*, in contrast to the exposure to SCs in TAZs with a larger proportion of low- or high-speed roads. Moreover, the population density and employment density were positively correlated with the SC frequency, which was consistent with the research of Abdel-Aty, et al. (2013) and Hadayeghi, Shalaby, and Persaud (2003). Regarding the layout of the transportation network, the major road density had a positive impact on the frequency of SCs, which was consistent with the findings of Aguero-Valverde and Jovanis

(2006). We also found that a larger number of simple intersections (3-way intersections) was directly related to a lower frequency of SCs. With regards to the destination accessibility, the bus stop density was positively correlated with the frequency of SCs, which was consistent with the research conducted by Kim, et al. (2010) on the SC frequency and similar to the research of Quddus (2008), who focused on the frequency of crashes that led to injuries. Moreover, the proportion of older adults was positively correlated with the SC frequency; these findings were consistent with the research reported by Wier, et al. (2009) in San Francisco, California, USA. The uneven geographical distribution of older adults in Wuhan has made this group particularly vulnerable to SCs. As Xie, Zhou, and Luo (2016) argued, a majority of these older adults are concentrated in the urban core in Wuhan, which is characterized by a high population density and dense commercial facilities. Accordingly, such groups that are in a stage of functional decline are exposed to a larger traffic volume; thus, they are more likely to be involved in crashes and to be more seriously injured. Previous research has suggested that a higher housing price is strongly associated with a larger household wealth (Aartolahti, Tolppanen, Lönnroos, Hartikainen, & Häkkinen, 2015), which in turn potentially contributes to variations in vehicle ownership, more prevalent motorized travel modes, and greater exposure to SCs at the area level (Najaf, et al., 2018). However, the relationship between the average housing price and SC frequency at the TAZ level remained unclear in this research.

Mediated by traffic volumes, the current research also identified several features that are indirect linked to the SC frequency; these features included the population density, employment density, major road density, bus stop density, car park density, and number of parks, all of which were deemed to be associated with trip generation and attraction. In contrast, in addition to land uses, traffic speeds did not act as mediators for the association between the frequency of SCs and the features involved in the GSEM. It should also be noted that the negative correlation between 3-way intersections and the SC frequency was mediated by neither traffic volumes nor traffic speeds. This finding might be attributed to reduced road conflict in addition to the setting of simple intersections. As Dumbaugh and Li (2010) argued, compared with complicated intersections, 3-way intersections provide better vision for pedestrians and drivers and thus help reduce vehicle-pedestrian crashes.

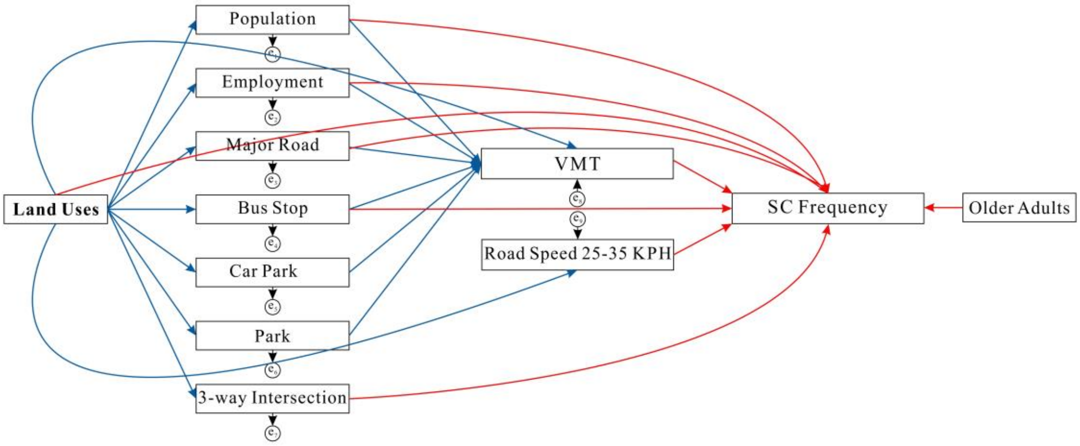


Figure 3 Path diagram for SCs in terms of land uses and SC-related features.

Note: the causal pathways of effects estimated based on the NB models are represented by red arrows, and those of effects estimated based on the linear models are represented by blue arrows. Pathways for error correlations are not displayed in the diagram.

Table 2 Model goodness of fit.

Model	CFI	GFI	RMSEA
Main model	0.484	0.768	0.243
Model that excluded insignificantly land-use-involved pathways	0.822	0.935	0.109
Model that excluded land use variables	0.938	0.977	0.073

Abbreviations: comparative fit index (CFI); goodness of fit index (GFI); root mean square error of approximation (RMSEA).

Table 3 Relationship between the SC frequency and SC-related features.

Dependent Variable		Independent Variable	Domain	Coeff.	Z-value	Significance
SC Frequency	←	VMT***	Traffic Volumes	0.380	4.674	<0.001
SC Frequency	←	Road Speed 25-35 KPH$^{\Psi}$	Traffic Speeds	0.099	1.722	0.085
SC Frequency	←	Employment Density*	Spatial Variation in Employment	0.139	2.273	0.023
SC Frequency	←	Population Density*	Spatial Variation in Population	0.173	2.432	0.015
SC Frequency	←	Major Road Density*	Layout of Transportation Network	0.109	2.097	0.036
SC Frequency	←	3-way Intersection$^{\Psi}$	Layout of Transportation Network	-0.102	1.845	0.065
SC Frequency	←	Bus Stop Density*	Destination Accessibility	0.211	2.290	0.022
SC Frequency	←	Older Adults*	Age Structure	0.110	2.086	0.037
VMT	←	Population Density***	Spatial Variation in Population	0.361	4.082	<0.001
VMT	←	Employment Density***	Spatial Variation in Employment	0.329	4.281	<0.001
VMT	←	Major Road Density***	Layout of Transportation Network	0.241	3.712	<0.001
VMT	←	Bus Stop Density*	Destination Accessibility	0.166	2.457	0.014
VMT	←	Car Park Density**	Destination Accessibility	0.184	2.807	0.005
VMT	←	Number of Parks*	Destination Accessibility	0.122	2.484	0.013

Note: all explanatory variables have been normalized. ${}^{\Psi}p<0.10$; ${}^{*}p<0.05$; ${}^{**}p<0.10$; ${}^{***}p<0.001$.

Abbreviation: vehicle miles travelled (VMT).

4.2. Variation in the SC frequency and reshaping crash-related features in land use conversions

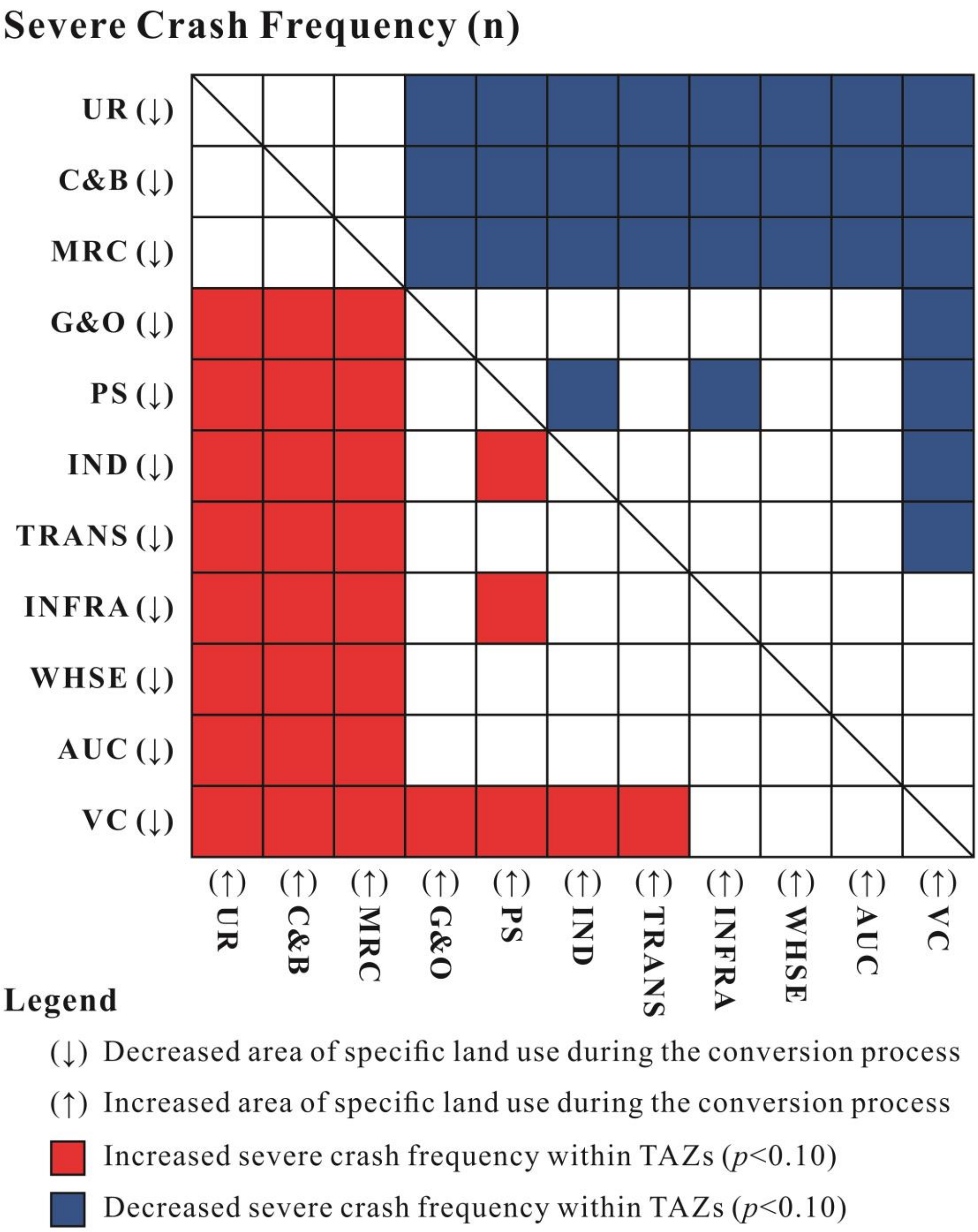
The variation in the SC frequency and the reshaping of SC-related features in land use conversions were examined using the Wald test based on the total effects of various land uses on the SC frequency/SC-related features. Ultimately, a total of 110 mutual conversion relationships were established. To provide a clear interpretation, the corresponding variations in the frequency of SCs are visualized in **Figure 4**, in which each row represents the reduction in a specific land use area in the conversions, and each column indicates an increment in a specific land use area within the TAZs. In this diagram, the red grids and blue grids denote an increase and decrease, respectively, in the SC frequency in the mutual conversions at a significance level of 0.10.

Our results showed that approximately 55% (i.e., 60 of 110) of the conversion relationships engendered variations in the zonal SC frequency. There were no significant variations in the TAZ SC frequency during the mutual conversions among areas devoted to government and office, industry, transportation, infrastructure, warehouse and districts under construction. In contrast, for four land use classes, namely, village construction, residential, commercial & business, and mixed residential-commercial areas, a set of related land use conversions had robust and broad impacts on the SC frequency; during these types of conversions, 83% (i.e., 56 of 68) of related land use conversions were associated with significant changes in the SC frequency at the TAZ level. At the expense of reducing areas devoted to all other 8 land use classes, increases in the areas of residential, commercial & business, and mixed residential-commercial land uses are correlated with a significant increase in the TAZ SC frequency; in summary, these 3 land use classes had the highest risks of exposure to SCs. This finding indicates that increasing the areas of other land uses and creating a delicately mixed land use structure within the districts dominated by residential, commercial and business, and mixed residential-commercial land uses might function as efficient countermeasures for zonal traffic safety improvements. In contrast, when converting from other land use classes, except for areas devoted to infrastructure, warehouses, and areas under construction, a corresponding increment in the area of village construction would cause negative variations in the SC occurrence within TAZs. Additionally, a noticeable increase in the SC frequency would occur when transforming areas devoted to infrastructure or industry into districts for public space, and vice versa.

Likewise, SC-related features during the abovementioned land use conversions were reshaped, and we gained new knowledge regarding the correlation between land use planning and road safety issues. As shown in **Figure 5**, reshaping the motorized traffic volume, destination accessibility, and spatial variations in the population and employment was largely driven by land use conversions that involved residential, commercial, and mixed residential-commercial land uses. Our findings confirmed our hypothesis that traffic volumes could be regarded as primary mediators linking land use conversions to the variation in SCs. In general, as they exacerbate the spatial agglomeration of features that are closely associated with travel demand, residential- and commercial-oriented land use conversions (i.e., three types of land use conversions aimed at expanding the areas of residential, commercial & business, and mixed residential-commercial land uses) are highly sensitive to the generation of activities and trips, thereby resulting in a higher risk of exposure to SCs. For example, **Table 4** indicates that the major features all experienced a reshaping process during the residential- and commercial-oriented land use conversions, and all 3 types of conversions were associated with significant increments in the population density and car park density within TAZs. Accordingly, a greater mixed traffic flow, more contact opportunities, and subsequently greater risks of exposure to both vehicles and pedestrians would be generated due to the agglomeration of the population and car parks.

Moreover, despite a similar increment in the frequency of SCs, a discrepancy existed in the reshaping features during these 3 types of conversions. For example, the bus stop density increased with increases in the unitary residential and commercial and business areas. However, such a trend was not found for the conversions that were oriented towards mixed residential-commercial land use. An increased employment density was universally correlated with an increment in the areas of commercial and mixed residential-commercial land uses, opposite to the trend for unitary residential-oriented conversions. Given the close association among the bus stop density, employment density, and diversified traffic volume (e.g., transit trips or walking trips), reshaping the traffic volume is more complex during land use conversions; consequently, single motorized traffic volume instead of a mixed traffic flow, including the flow from pedestrian to cyclist to vehicle, might not fully capture this correlation.

In addition, the results showed that reshaping the traffic speeds corresponded only to a few sets of conversions without a clearly regular pattern and indicated that macro-level land use conversions were less associated with the reshaping or re-regulation of zonal traffic speeds. This issue might be attributed to two reasons: first, “one-size-fits-all” zonal traffic speed regulations have come to dominate urban China; second, controls on traffic speeds might be largely regulated by location-specific traffic-calming countermeasures or targeted engineering practices that are predominately independent of the influences of land use conversions.



	(↑) UR	(↑) C&B	(↑) MRC	(↑) G&O	(↑) PS	(↑) IND	(↑) TRANS	(↑) INFRA	(↑) WHSE	(↑) AUC	(↑) VC
UR (↓)				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
C&B (↓)				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
MRC (↓)				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
G&O (↓)	🟥	🟥	🟥								🟦
PS (↓)	🟥	🟥	🟥			🟦		🟦			🟦
IND (↓)	🟥	🟥	🟥		🟥						🟦
TRANS (↓)	🟥	🟥	🟥								🟦
INFRA (↓)	🟥	🟥	🟥		🟥						
WHSE (↓)	🟥	🟥	🟥								
AUC (↓)	🟥	🟥	🟥								
VC (↓)	🟥	🟥	🟥	🟥	🟥	🟥	🟥				

Figure 4 Variations in the frequency of TAZ SCs during land use conversions.

Abbreviations: urban residential (UR); commercial and business (C&B); mixed residential-commercial (MRC); government and office (G&O); public space (PS); industrial (IND); transportation (TRANS); infrastructure (INFRA); warehouse (WHSE); area under construction (AUC); village construction (VC). Each row represents a reduction in a specific land use area during the conversion process, and each column indicates an increment in a specific land use area within the TAZs.

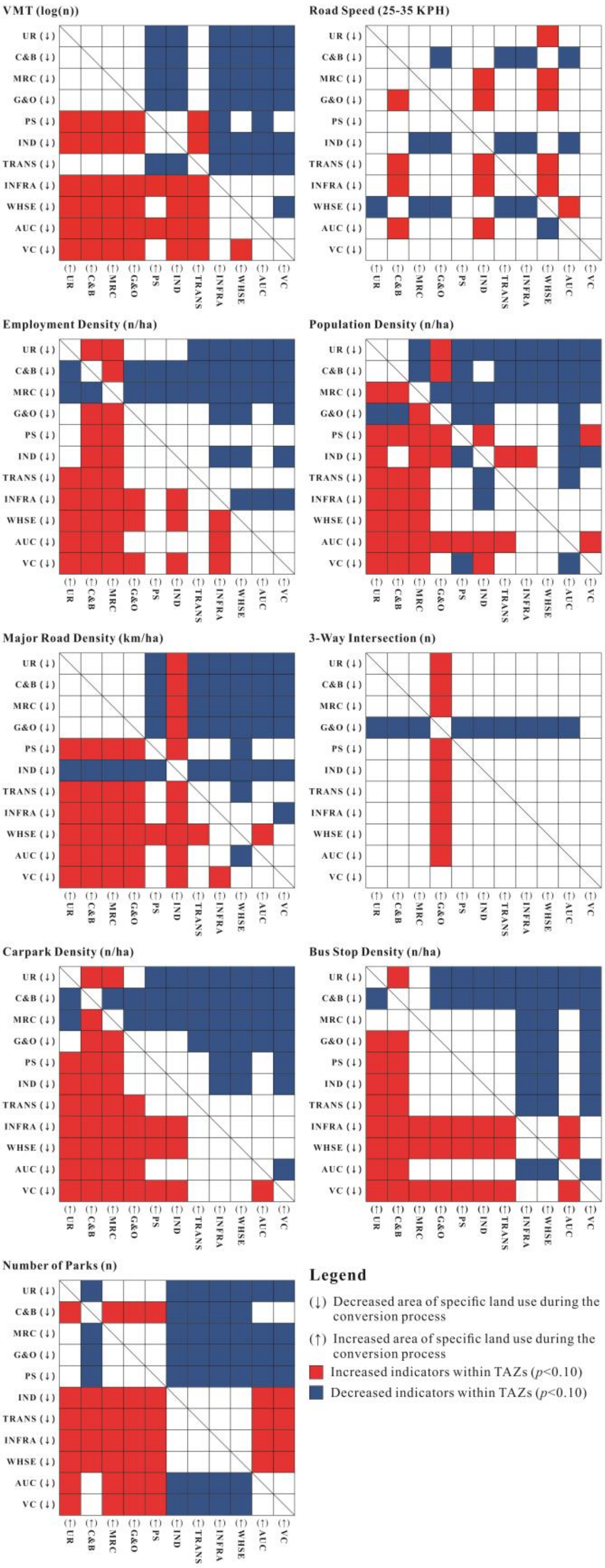


Figure 5 Reshaping SC-related features during land use conversions.

Abbreviations: urban residential (UR); commercial and business (C&B); mixed residential-commercial (MRC); public space (PS); industrial (IND); transportation (TRANS); infrastructure (INFRA); warehouse (WHSE); area under construction (AUC); village construction (VC). Each row represents a reduction in a specific land use area during the conversion process, and each column indicates an increment in a specific land use area within the TAZs.

Table 4 Reshaping the major features during residential- and commercial-oriented land use conversions.

Land use conversions	Major reshaping features at the TAZ level	Number of involved conversions
G&O, PS, IND, TRANS, INFRA, WHSE, AUC, VC→UR	VMT (+)	6
	Population density (+)	7
	Road density (+)	6
	Car park density (+)	7
	Bus stop density (+)	8
	Number of Parks (+)	6
G&O, PS, IND, TRANS, INFRA, WHSE, AUC, VC→C&B	VMT (+)	6
	Population density (+)	6
	Employment density (+)	8
	Road density (+)	6
	Road speed 25-35 km/h (-)	4
	Car park density (+)	8
	Bus stop density (+)	8
	Number of Parks (+)	4
G&O, PS, IND, TRANS, INFRA, WHSE, AUC, VC→MRC	VMT (+)	6
	Population density (+)	7
	Employment density (+)	8
	Road density (+)	6
	Car park density (+)	8
	Number of Parks (+)	6

Note: → denote unidirectional land use conversions. (+) and (-) indicate an increment and a reduction, respectively, in SC-related features.

Abbreviations: urban residential (UR); commercial and business (C&B); mixed residential-commercial (MRC); government and office (G&O); public space (PS); industrial (IND); transportation (TRANS); infrastructure (INFRA); warehouse (WHSE); area under construction (AUC); village construction (VC).

4.3. Implications for land use planning and road safety promotion

Over the last two decades, the shift in land system reform and the institutional changes from a central planning perspective to a market orientation have drastically benefitted the urban land markets in China (Zhu, 2005). In pursuit of economic benefits, large land parcels have been packaged and uniformly leased out to developers by local governments, resulting in relative single and low mixed development patterns that primarily combine residential, retail and business functions (Shin, 2014). Nevertheless, as indicated by our findings, these development patterns have dramatically increased the spatial agglomeration of the employment and population and the accessibility to destinations, resulting in larger and more mixed traffic volumes. Moreover, in the majority of land use conversions, zonal traffic speeds also seem to be lacking effective and stringent regulations. Under such circumstances, it is frustrating to admit that hidden dangers for road safety would be *inevitably* exacerbated. With the intensifying conflict between the growing demands for residential and commercial land resources associated with increasing traffic risks, the road safety in urban China will continue to deteriorate without explicit and preventive strategies that incorporate traffic safety considerations into land use planning.

Our approach could be used to assess, *ex ante*, the potential safety outcome of land use conversion strategies in not only urban China but also other transitional cities. Although the pre-assessment results might vary with changes in focal cities and actual planning practices are much more complex, the proposed approach has a relatively extensive applicability. According to the pre-assessment, urban planners could devote more efforts to siting and allocating high-risk land parcels to avoid unplanned road dangers to relatively large districts. Under circumstances without alternatives (e.g., converting old villages into urban residential areas coincident with urban expansion), urban planners could also be aware of the potential surge in road hazards and accordingly construct targeted countermeasures to offset the negative consequences in advance. For example, considering the weak association between land use conversions and reshaped zonal traffic speeds, there is an urgent need to formulate efficient zonal traffic speed regulations to weaken the negative effects of high-risk conversions in urban China.

5. Conclusion

This article presented an approach to pre-assess the road safety outcomes of land use conversion strategies by investigating the hierarchical relationship among land use conversions, reshaped SC-related features, and variations in SCs. Using GSEM and the Wald test, land use conversion relationships were constructed, and the corresponding variations in the SC frequency at the TAZ level were examined. Three land use classes were identified at the highest level in terms of the risk of exposure to SCs: urban residential, commercial and business, and mixed residential-commercial land uses. A set of land use conversions aimed at enlarging the areas of these three land uses was positively associated with the frequency of SCs at the TAZ level. Our research also revealed that the reshaping of SC-related features was closely associated with land use conversions. The reshaping of motorized traffic volumes, spatial variations in the employment and population, and accessibility to destinations were primarily driven by residential- or commercial-oriented land use conversions, indicating that these types of conversions largely exacerbate the agglomeration of high-risk SC-related features and are highly sensitive to the generation of mixed traffic flows, leading to a higher risk of exposure to SCs. In contrast, land use conversions were less associated with the reshaping of zonal traffic speeds. The proposed approach and the corresponding findings could be used to support land use planning strategies for improving the traffic safety and controlling SCs in transitional cities and urban China in particular. According to the pre-assessment results, urban planners could become aware of the potential variations in road hazards associated with conversion strategies; accordingly, they could pay more attention to siting and allocating high-risk land parcels and to crafting targeted countermeasures in advance.

Our study also had some limitations. First, regarding the data constraints, to protect the privacy of the injured, the SC data provided by WEMMC do not contain detailed information about the severity of the injury, although the effects of different land uses on different crashes divided by the injury severity might vary. The traffic volume variable (i.e., VMT) contained only motorized flow; as shown in our results, reshaping the traffic volume would be more complex during land use conversions. Geometric factors of the road design (e.g., road width and road curvature) were not considered comprehensively due to restrictions in the data. Second, the pre-assessment of land use conversions was implemented based on cross-sectional research design. Third, this study did not adequately take into account the emerging traffic safety equity issue in developing countries, which focuses on guaranteeing equal access to traffic safety resources across diversified population groups (Najaf, Isaai, Lavasani, & Thill, 2017). Therefore, future studies should employ SC data involving detailed severity information, diversified traffic volumes and road design variables to establish a comprehensive association between land use conversions and road safety. Longitudinal design could be developed to investigate the dynamic relationships between land use conversions and variations in SCs. Moreover, considering the remarkable variations in socioeconomic status, living environment, travel demand, and travel pattern among citizens in transitional cities, traffic safety inequity potentially ensues from policy implementation and planning practices; accordingly, the issue of incorporating traffic safety equity consideration into the evaluation of land use planning strategies deserves to be further explored.

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