Effects of the built environment on automobile-involved pedestrian crash frequency and risk

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A B S T R A C T

This area-based study explores the relationship between automobile-involved pedestrian crash frequency versus risk and various built environment factors, such as road network and land use. The methodology involves the use of Bayesian hierarchical intrinsic conditional autoregressive model, which accounts for unobserved heterogeneities and spatial autocorrelations. The city of Seattle is selected for this empirical study, and the geospatial unit of analysis is traffic analysis zone. The primary data were obtained from Seattle Department of Transportation collision profiles. The major findings of this research include: (1) the densities of 4-way intersections and more than 5-way intersections, and land use mixture are positively correlated with the pedestrian crash frequency and the risk; (2) sidewalk density and the proportion of steep areas are negatively associated with the pedestrian crash frequency and the risk; (3) areas with a higher bus stop density are likely to have more pedestrian crashes; (4) in areas with a greater proportion of industrial land use, the pedestrian crash frequency is lower; (5) in areas with an averagely higher posted speed limit, the pedestrian crash risk is higher; (6) in areas with a greater employment density, the pedestrian crash risk is lower; (7) the mode share of walking and the total number of trips are positively correlated with the pedestrian crash frequency, and the total number of trips is negatively correlated with the pedestrian crash risk. These findings provide supports for planning policy making and road safety programs. Local authorities should improve walkability through providing more sidewalks and separate motorized traffic and pedestrian travels in areas with different land use purposes. Compact development should be encouraged to support building a safe walking environment.

Keywords:
Pedestrian crash frequency, pedestrian crash risk, built environment, spatial autocorrelation, roadway design

1. Introduction

Walking is an environmentally friendly and healthy transportation mode. Its intrinsic value can never be over-exaggerated. That is also why walking has been a lasting mode of travel and should be so in the future. However, in the process of urbanization and motorization, walking tends to be devalued to such a degree that it has become more vulnerable than ever, even in developed countries like the US (The National Highway Traffic Safety Administration, 2012). As car dependence increased, pedestrian travel has gradually stepped down as an unpopular mode choice. From 1980 to 2010, the percentage of walking commuters in the US, for instance, steadily decreased from 5.60% to 2.77% (American Association of State Highway and Transportation Officials and US Department of Transportation, 2013). For work-related trips, walking is mostly unattractive. However, as obesity rate grows, as a mode encouraging physical activity, the importance of walking is gradually realized across nations and much has been done to promote walking (Frank and Engelke, 2001; Pucher and Buehler, 2010). Walking is largely advocated by the public, because it has great potential to mitigate environment and health challenges that our society is facing (Newman and Kenworthy, 2006; Saelens et al., 2003).

Policy makers and urban planners advocate developing new urbanist communities that promote sustainable cities through encouraging smaller lot size, more mixed land use, denser blocks, and greater street connectivity (Ellis, 2002; Lee and Moudon, 2006; Lund, 2003). The livable neighborhoods have better proximity to amenities, such as open spaces, parks, grocery stores, and jobs, which contribute to a greater mode share of walking (Ellis, 2002; Lund, 2003). Ideally, the popularity of walking could be greatly enhanced by improved pedestrian safety and well-planned walking environments. Therefore, the attractiveness of walking has been highlighted in the ideas of new urbanism and smart growth (Ellis, 2002; Lund, 2003). However, the role of pedestrian safety is still paid little attention.

Pedestrians are actually vulnerable road users. For instance, in the US, 4,743 pedestrians were killed and 76,000 pedestrians were injured in 2012, and pedestrian deaths accounted for 14% of all traffic fatalities (The National Highway Traffic Safety Administration, 2012). Policy makers have been undertaking efforts to promote safe walking environments. Taking Seattle as an example, the Seattle Department of Transportation issued a pedestrian master plan to develop strategies to decrease the number of pedestrian collisions and severe injuries. The proposed countermeasures included maintaining pedestrian visibility at intersections, improving crossing conditions, and regulating driving speed limits (Seattle Department of Transportation, 2009).

The role of the built environment in explaining the causes of pedestrian crashes has been continually investigated (The National Highway Traffic Safety Administration, 2012). Existing studies have linked aspects of the road network and pedestrian safety across different spatial scales. For micro-level studies, an overall finding is that intersections have more pedestrian crashes because there are more conflict points among travelers and vehicles (Ukkusuri et al., 2012). The importance of conducting micro-level research is that its results can efficiently inspire countermeasures for safety improvements. However, micro-level studies only catch the intersection or midblock characteristics as pieces of road elements, while macro-level studies understand a city as a complex system. In addition, specific crash site's location is often "scaled up" to an intersection or midblock in practice. Therefore, corresponding built environment features often lack accuracy, and fixed covariates could be biasedly measured when road features along a road segment are not constant. Area-based studies examine the relationship between the built environment and pedestrian crashes at a larger geospatial scale where data are richer and more accurate, which help produce more stable estimates, and capture aggregated effects of more covariates on pedestrian crashes and related risks.

This study contributes to the existing studies on the following three aspects. First, this study innovatively includes travel demand forecasted number of pedestrian trips as a denominator to measure pedestrian crash risk. Also, this study compares the variation between a frequency model versus a risk model, targeting to provide a more objective understanding on pedestrian safety. Second, by examining the effects of several commonly used density measures, this study testifies the generalizability of the theory of safety in numbers in a US urban setting. Third, this study considers the spatial spillover effects across the urban space at an area level regarding pedestrian crash frequency versus risk. Building on existing studies, this study is designed to identify the effects of land use and road network features on pedestrian safety.

To this end, the purpose of this study is to investigate what built environment factors are associated with pedestrian crash frequency versus pedestrian crash risk at a macro-level. This study considers quite a few area-based covariates that have not been considered before in existing studies, such as travel demand forecast. Two Bayesian hierarchical intrinsic conditional autoregressive (ICAR) models accounting for unobserved heterogeneities and spatial autocorrelations are conducted to evaluate the pedestrian crash frequency and the risk across traffic analytical zones (TAZs) in Seattle, Washington. The hypothesis of this study is that compact developed urban environment is safer. Though a higher pedestrian crash frequency could be observed in dense urban settings, the pedestrian crash risk could be actually lower. The independent variables include various factors of the road network, land use, socio-demographics, and travel demand. This paper begins with a literature review and research design, follows by methodological details, and then presents the results of the ICAR models, and ends with conclusions, a discussion, and future research.

2. Literature Review

Conventionally, traffic engineers and health professionals use the 5E's and the Haddon's Matrix to analyze crash and injury outcomes, and to propose safety improvement strategies. The 5E's analytical tool refers to Environment, Engineering, Enforcement, Education, and Emergence Aid (Bergman et al., 2002; Morrison et al., 2003). The Haddon's Matrix, as a standardized framework, is made of Host, Agent, Event, and Environment (Runyan, 2015). Both of these conceptual models highlight the importance of the built environment in explaining pedestrian crashes occurred in urban settings.

Key Definitions

In most cases, a "pedestrian crash" refers to an automobile intersecting with a pedestrian. "Crash frequency" is the number of collisions at a certain location per unit time. "Crash risk" is often calculated by the number of collisions reported per 1,000 trips, 1,000 hours, or 1 kilometer of exposure (de Geus et al., 2012).

Effects of Built Environment Factors

As aforementioned, the built environment plays an important role in explaining crash and injury outcomes. A number of studies have examined the relationship between built environment factors and pedestrian crash frequency versus risk at multiple geospatial scales. The scales include signalized intersections (Miranda-Moreno et al., 2011; Pulugurtha and Sambhara, 2011), state or city routes (Moudon et al., 2008; Moudon et al., 2011), census tracts (Narayanamoorthy et al., 2013; Ukkusuri et al., 2011; Ukkusuri et al., 2012; Wang and Kockelman, 2013; Wier et al., 2009), zip code boundaries (Ukkusuri et al., 2011; Ukkusuri et al., 2012), and TAZs (Siddiqui et al., 2012). For studies done at the point or the polyline level, such as intersections and state routes, a commonly observed bias is that those studies cannot cover all geographical areas. For example, intersection-based studies cannot identify risk factors of pedestrian collisions that occurred at mid-blocks. The unit of analysis varies greatly across the prior studies.

Though area-based research produces more stable estimates, it also has the threat of "regression towards the mean" due to aggregation. Variables quantified at a larger scale are relatively constant, and are easy to match other census information, such as household density, employment density, and travel demand. However, the preciseness of built environment measurements can be diluted due to aggregation. Some localized built environment features can only be identified at a smaller scale. In other words, a smaller geo-spatial unit is preferred in the analysis to avoid the threat of "regression towards the mean".

Regarding road network features, the densities of local streets and sidewalks are negatively associated with the number of pedestrian crashes (Miranda-Moreno et al., 2011; Siddiqui et al., 2012; Wang and Kockelman, 2013), indicating that facilitating pedestrians through sidewalk provisions and local street densifications decrease the number of crashes. On the contrary, arterial density is positively correlated with pedestrian crash frequency (Miranda-Moreno et al., 2011; Siddiqui et al., 2012; Wang and Kockelman, 2013; Wier et al., 2009). The existing findings on the effects of freeway or highway density on pedestrian crash frequency were mixed, both positive (Wang and Kockelman, 2013) and negative (Miranda-Moreno et al., 2011; Moudon et al., 2011; Narayanamoorthy et al., 2013) associations were identified. Because pedestrians are not allowed to walk on freeways and highways, those relationships could be case-specific correlations rather than casual relations. A greater transit route density and a better transit service were reported to correlate with more pedestrian crashes (Miranda-Moreno et al., 2011; Ukkusuri et al., 2012; Wang and Kockelman, 2013).

In particular, the effects of intersection characteristics on pedestrian crashes were also examined in the existing studies. The densities of signals, crosswalks (Moudon et al., 2011), 4-way and 5-way intersections (Pulugurtha and Sambhara, 2011; Siddiqui et al., 2012; Ukkusuri et al., 2012) were positively correlated with pedestrian crash frequency. Interestingly, a study found that a greater number of 3-way intersections was associated with fewer pedestrian crashes (Ukkusuri et al., 2012).

In terms of land use features, studies suggested that higher proportions of commercial land use (Miranda-Moreno et al., 2011; Moudon et al., 2008; Narayanamoorthy et al., 2013; Ukkusuri et al., 2011; Wang and Kockelman, 2013; Wier et al., 2009) and offices

(Narayanamoorthy et al., 2013) are correlated with more pedestrian crashes. But the findings on residential land use were not in an agreement within the prior studies. Ukkusuri et al.'s studies indicated that residential land use was negatively associated with pedestrian crash frequency (2011, 2012), whereas a positive association was identified between the number of dwelling units and pedestrian crashes in Siddiqui et al.'s study (2012). Miranda-Moreno et al.'s study suggested that the effects of residential land use on pedestrian crashes were not constant as the radius of signalized intersection buffers changed (2011). The findings on industrial land use and open space were varied. Both positive (Ukkusuri et al., 2012) and negative (Miranda-Moreno et al., 2011) associations had been identified in the prior research. More mixed land use was associated with fewer pedestrian crashes (Wang and Kockelman, 2013). A short summary for the effects of land use factors on pedestrian crash frequency is that many relationships were not consistent across previous empirical studies.

The issue of students' walking safety had been emphasized in the prior studies. Since students have a higher propensity of involvement in pedestrian crashes, a few studies included the number of, the proximity to, and the density of schools for modeling. School density suggested a positive relationship with the number of pedestrian crashes (Narayanamoorthy et al., 2013; Ukkusuri et al., 2011; Ukkusuri et al., 2012), but parcels with higher proximities to schools showed a negative association with pedestrian crashes (Wang and Kockelman, 2013). These conclusions indicate that pedestrian crashes are apt be occur around school areas. However, the likelihood of involving a pedestrian crash is decreasing when homes to schools are approximating. Interestingly, the coefficients estimated for school density changed with the size of signalized intersection buffers in Miranda-Moreno et al.'s study (2011).

With regards to socio-demographic factors, areas with higher employment density (Pulugurtha and Sambhara, 2011) and population density (Moudon et al., 2011; Pulugurtha and Sambhara, 2011; Ukkusuri et al., 2012; Wang and Kockelman, 2013; Wier et al., 2009) were positively correlated with the number of pedestrian crashes.

In relation to travel demand, traffic volume was a key exposure variable in understanding the pedestrian crashes (Roberts et al., 1992; Stevenson et al., 1995). A few studies confirmed that either traffic volume or vehicle miles traveled was positively correlated with pedestrian crashes (Miranda-Moreno et al., 2011; Wang and Kockelman, 2013; Wier et al., 2009). The other commonly used exposure measurements for pedestrian crashes included walking mode share (Narayanamoorthy et al., 2013), pedestrian volume (Miranda-Moreno et al., 2011; Pulugurtha and Sambhara, 2011), and the total number of crashes (Moudon et al., 2008; Moudon et al., 2011). Prior research showed a consistent result that pedestrian volume had a positive association with crash frequency (Miranda-Moreno et al., 2011; Pulugurtha and Sambhara, 2011).

It is worth noting that pedestrian crash risk was less often investigated relative to pedestrian crash frequency, because the measurements representing pedestrian volume data, such as the number of pedestrian trips, pedestrian miles traveled, and pedestrian hours traveled, are mostly unavailable.

3. Research Design

3.1 Data Source

This study examines how built environment factors are correlated with pedestrian crashes and risks at an area-based macro level. Built environment features are quantified by factors of road network and land use. Some previously under-investigated factors, such as density of stop signs, the proportion of steep areas, and zonal average posted speed limit are included in this study.

This research uses data from two major components, pedestrian crash records and built environment features. The pedestrian crash records are obtained from Seattle Department of Transportation (SDOT) during the period from January 2008 to December 2012. There are in total 2,186 geocoded pedestrian crashes. The crash risk is measured by the number of pedestrian crashes divided by the origin and destination-based forecast of the number of walking trips in each TAZ accordingly. The number of walking trips and the total number of trips are the major output of a regional activity-based travel demand model, called SoundCast (Puget Sound Regional Council, 2014). The other data were obtained from three agencies, including SDOT, King County, and the Puget Sound Regional Council. TAZ is selected as the unit of analysis because it matches the existing travel demand output and quantifies the built environment factors at a relative small geospatial scale. The built environment feature quantification is done using ArcGIS overlay functions. *Table 1* defines the selected variables and includes a data summary.

3.2 Variable Selection

This study initially has considered a large set of variables for modeling. However, many variables are dropped for highly correlating with other fixed covariates. Variables excluded for collinearity are signal density, street parking sign density, crosswalk density, transit route density, and street lane density. Additionally, some variables are not considered due to incomplete spatial coverage. For example, traffic volume, the number of lanes, and street width are only available to be measured at arterials for Seattle's data.

3.3 Methodology

The Bayesian hierarchical intrinsic conditional autoregressive model has been frequently employed in recent area-based crash studies. The flexibility in structuring complicated models and the ability to account for unobserved heterogeneities and spatial autocorrelations contribute to its popularity. A 3-stage hierarchical Bayesian inference is done in the process of estimation. In the first stage, a Poisson process is employed to model the observed area-based pedestrian crash frequency versus the risk that is measured by the TAZ-based number of pedestrian trips. In the second stage, both of the pedestrian crash frequency and the risk are specified as functions of explanatory variables and random effects. In the third stage, the unknown parameters are assigned according to their prior distribution. The Poisson process for the pedestrian crash frequency and the risk are specified as *Eqs. (1) and (2)*:

$$Y_i|\theta_i \sim Poisson(\theta_i) \tag{1}$$

$$Y_i|\theta_i \sim Poisson(E_i\theta_i) \tag{2}$$

Where Y_i is the number of pedestrian crashes in TAZ_i, θ_i is the joint distribution of explanatory factors and random effects in TAZ_i, and E_i is the forecasted number of walking trips in TAZ_i. The logs of the risk factors and random effects are modeled in the second stage, as shown in *Eq. (3):*

$$log\ (\theta_i) = \alpha + \beta_i X_i + V_i + U_i \tag{3}$$

Where X_i represents a vector of explanatory variables, β_i is a vector of estimated parameters, α is the intercept, V_i is the unobserved heterogeneity and U_i is the spatial dependence. The prior distribution for the unobserved heterogeneity V_i is given as *Eqs. (4) and (5).*

$$V_i \sim N(0, {\sigma_v}^2) \tag{4}$$

$${\sigma_v}^{-2} \sim Ga(0.5, 0.0005) \tag{5}$$

The spatial autocorrelation, U_i, is specified as if the values of the spatial random effects U_j in neighboring areas are known. Under the ICAR's specification, the spatial random effects are drawn from a normal distribution whose mean is based on their neighbors, with variances proportional to the number of neighbors. Therefore, TAZs with more neighbors have less variability. *Eqs. (6) and (7)* show the distribution of the random effect for capturing spatial autocorrelations.

$$U_i|U_j, j \in ne(i) \sim N(\bar{U}_J, \frac{{\sigma_u}^2}{m_i}) \tag{6}$$

$$\bar{U}_J = \frac{1}{m_i}\sum_{j \in ne(i)} U_j \tag{7}$$

Where *ne(i)* is the set of neighbors of TAZ_i, and m_i is the number of neighbors, $\bar{U}_J$ is the mean spatial random effects of its neighbors, ${\sigma_u}^2$ is a conditional variance, and its magnitude determines the amount of spatial variation. σ_u and σ_v control the amount of extra variability of the Poisson process, which is allocated to the unobserved heterogeneity and the spatial spillover effect among adjacent TAZs. The proportion of the variance explained for spatial autocorrelations by the two random effects is calculated by *Eq. (8).*

$$\theta = \frac{Var(U)}{Var(U)+Var(V)} \tag{8}$$

4. Results

4.1 Descriptive analysis

Table 1 presents the data summary of selected variables for modeling. The dependent variable of the frequency model is the number of pedestrian crashes that occurred in the 5-year period, ranging from 0 to 27 observations with a mean of 2.50 in 863 TAZs, as shown in *Figure 1*. The exposure variable in the crash risk model is the TAZ-forecasted number of walking trips, ranging from 1 to 7,212 with a mean of 553.95 trips, as shown in *Figur 2*. As noted from the two figures, after adjusting the forecasted walking trips, the spatial patterns of the pedestrian crash frequency and the risk are varied greatly in the two figures.

4.2 Inferential analysis

This section summarizes the results for the Poisson log-normal ICAR models applied to the 5-year pedestrian crash data. *Table 2* presents the modeling estimates for the relationships between built environment factors and the pedestrian crash frequency versus the risk. The estimates of the marginal variance for the unobserved heterogeneity (V_i) and clustering effects among adjacent zones (U_i) are used to calculate the proportion of variance in the random effects to quantify the spatial dependence. The proportions of the spatial spillover effect are 31.07% in the pedestrian crash frequency model and 17.05% in the risk model. These indicate that the variability in the random effects cannot be explained by spatial autocorrelations in these two models. Spatial autocorrelation is not a major concern when modeling the relationships between the built environment and pedestrian crash versus risk at an area level regarding Seattle's data.

To further interpret the results estimated by the two ICAR models, coefficients with no possible zero estimates within the credible intervals (2.50% CI to 97.5% CI) are counted as significant effects, marked *"Italic"* in *Table 2*.

Regarding the estimates, in relation to road network factors, the densities of 4-way intersections and more than 5-way intersections are positively associated with the pedestrian crash frequency and the risk. Bus stop density is only positively associated with the pedestrian crash frequency. In contrast, the sidewalk density and the proportion of steep areas suggest negative associations with the pedestrian crash frequency and the risk. When it comes to the land use variables, the pedestrian crash frequency is positively correlated with land use mixture, but negatively correlated with the proportion of industrial land use. The pedestrian crash risk is also positively correlated with land use mixture. For travel demand forecast, walking mode share is positively correlated with the pedestrian crash frequency. The total number of trips is positively correlated with the pedestrian crash frequency but negatively associated with the pedestrian crash risk.

Table 1

Variable definitions and data summary of predictors for the pedestrian crash frequency and the risk in Seattle TAZs (n = 863) average.

	Mean	SD	Min	Max	Description	Source
Dependent Variable:						
Pedestrian Crash Frequency	2.50	3.46	0.00	27.00	Number of pedestrian crashes	SDOT
Pedestrian Crash Risk	0.01	0.07	0.00	2.00	Number of pedestrian crashes/Forecasted number of pedestrian trips	PSRC
Fixed Effects:						
3-way Intersection	0.32	0.28	0.00	2.92	Number of 3-way intersections/zonal area (1/ha)	SDOT
4-way Intersection	0.44	0.34	0.00	3.26	Number of 4-way intersections/zonal area (1/ha)	SDOT
5-way Intersection	0.04	0.13	0.00	1.33	Number of more than 5-way intersections/zonal area (1/ha)	SDOT
Sidewalk Density	17.51	5.98	0.76	46.48	Sum of sidewalk length/zonal area (1km/km^2)	SDOT
Steep Area Proportion	0.02	0.04	0.00	0.25	Proportion of steep areas (0~1)	PSRC
Bus Stop Density	0.24	0.43	0.00	2.97	Number of bus stops/zonal area (1/ha)	King County
Zonal Speed Limit	25.00	4.68	20.00	51.73	Zonal-mean posted driving speed limit [mph]	SDOT
Household Density	0.23	0.35	0.00	5.40	Number of households/zonal area (1k/ha)	PSRC
Employment Density	0.79	2.11	0.00	20.86	Number of employments/zonal area (1k/ha)	PSRC
Land Use Mix[1]	0.47	0.20	0.00	0.95	Entropy of five types of land use (0~1)	PSRC
Commercial Land	0.09	0.15	0.00	0.88	Proportion of commercial and mixed land use	PSRC
Government & Office	0.09	0.15	0.00	0.90	Proportion of office and government land use	PSRC
Parks	0.05	0.13	0.00	0.92	Proportion of public parks	SDOT
Industrial	0.07	0.14	0.00	0.95	Proportion of industrial land use	SDOT
School Density	0.01	0.04	0.00	0.50	Number of schools/zonal area (1/ha)	SDOT
Activity Center Density	0.07	0.15	0.00	1.18	Number of activity centers/zonal area (1/ha).	SDOT
Walking mode share	0.17	0.11	0.02	0.50	Proportion of pedestrian trips divided by total number of trips (0~1)	PSRC
Number of Trips	7.00	5.02	0.00	61.10	Total number of trips (1k)	PSRC

Considered but excluded variables						
Transit Route Density	*0.89*	*0.86*	*0.00*	*5.95*	*Sum of transit route length/zonal area (1km/km^2)*	*King County*
Street Lane Density	*10.70*	*4.29*	*0.20*	*36.65*	*Sum of street length/zonal area (1km/km^2)*	*SDOT*
Crosswalk Density	*0.68*	*1.18*	*0.00*	*11.70*	*Number of crosswalks/zonal area (1/ha)*	*SDOT*
Average Slope	*3.47*	*1.88*	*0.01*	*11.74*	*Zonal-mean gradient*	*SDOT*

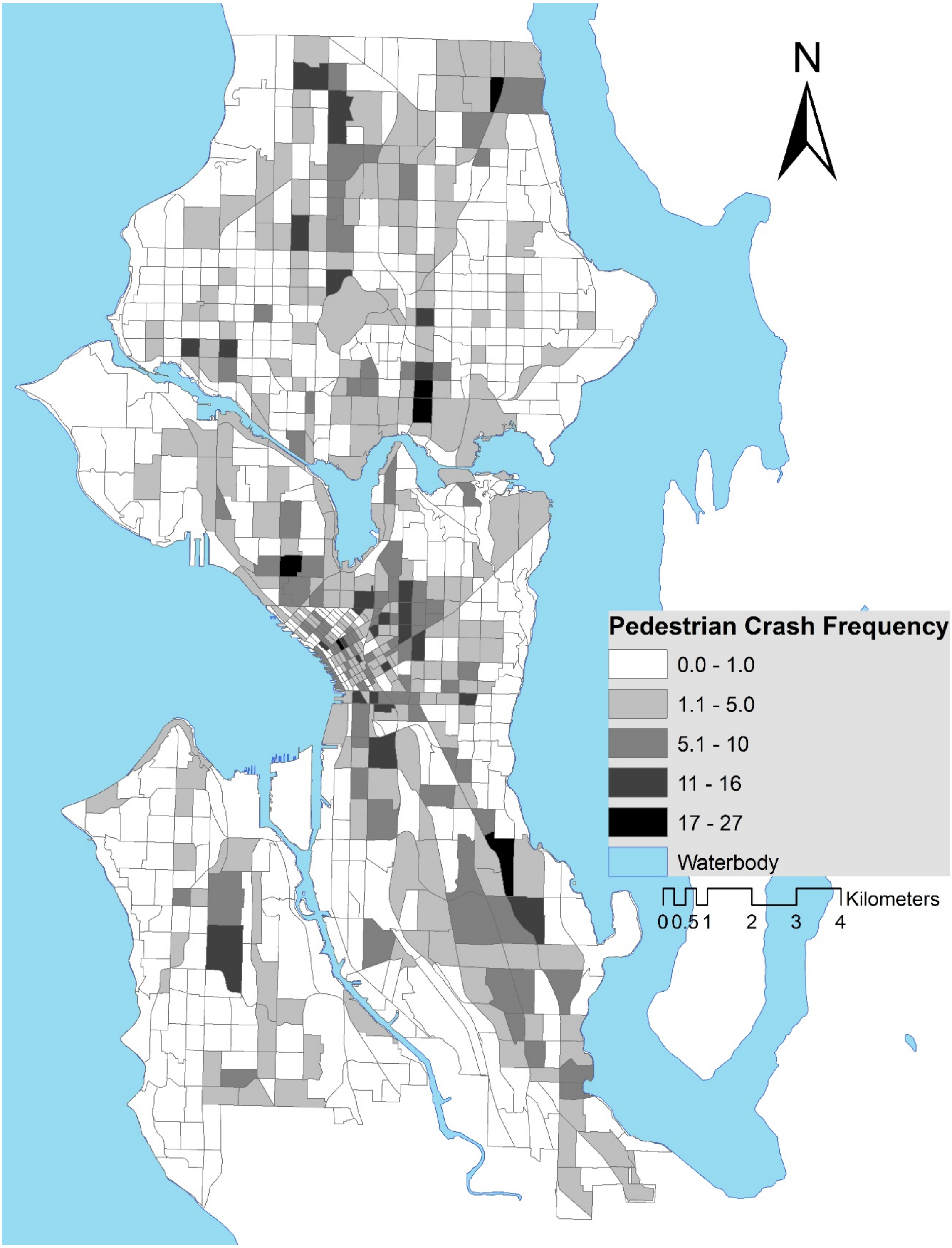

Fig. 1. The pedestrian crash frequency in Seattle TAZs, 2008~2012.

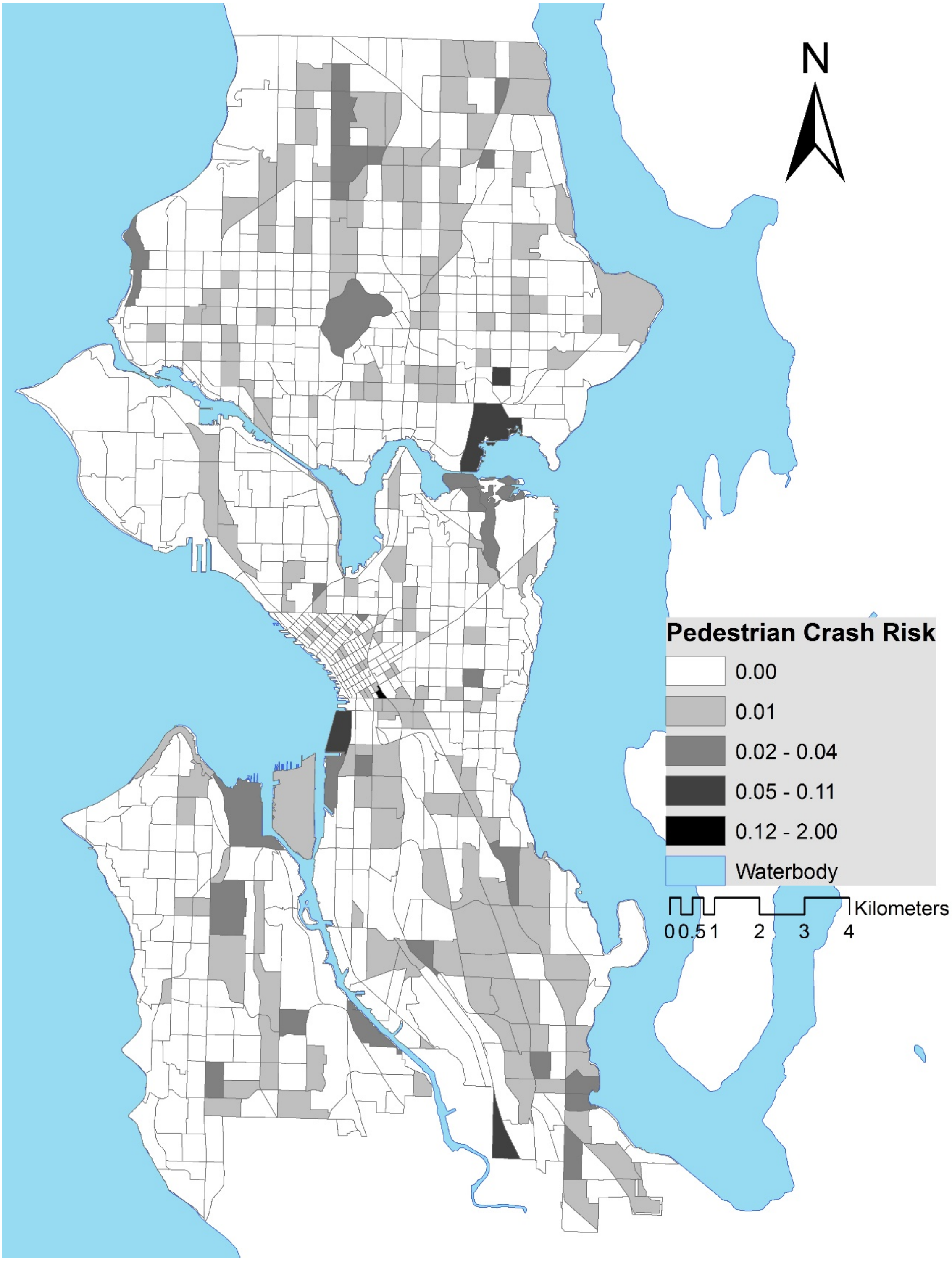

Fig. 2. The pedestrian crash risk in Seattle TAZs, 2008~2012.

Table 2

The estimates of Poisson-lognormal ICAR models (frequency versus risk) with 5-year pedestrian crash data.

	Pedestrian Crash Frequency Model			Pedestrian Crash Risk Model		
Fixed effects:	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI
Intercept	-1.56	-2.38	-0.75	-6.88	-7.69	-6.09
3-way Intersection	0.03	-0.28	0.34	0.05	-0.27	0.37
4-way Intersection	*0.45*	*0.11*	*0.79*	*0.53*	*0.19*	*0.87*
5-way Intersection	*0.82*	*0.26*	*1.39*	*0.94*	*0.36*	*1.51*
Sidewalk Density	*-0.03*	*-0.05*	*-0.01*	*-0.04*	*-0.07*	*-0.02*
Steep Area Proportion	*-5.72*	*-8.81*	*-2.73*	*-5.57*	*-8.65*	*-2.58*
Bus Stop Density	*0.34*	*0.02*	*0.66*	0.28	-0.04	0.60
Stop Sign Density	-0.07	-0.30	0.16	-0.03	-0.26	0.19
Zonal Speed Limit	0.01	-0.01	0.03	*0.03*	*0.01*	*0.05*
Household Density	-0.08	-0.37	0.21	-0.22	-0.52	0.07
Employment Density	-0.04	-0.08	0.01	*-0.05*	*-0.10*	*-0.01*
Land Use Mix[1]	*2.05*	*1.48*	*2.62*	*1.41*	*0.85*	*1.98*
Commercial Land	0.29	-0.44	1.03	0.58	-0.12	1.28
Government & Office	-0.54	-1.23	0.15	-0.48	-1.15	0.20
Parks	0.32	-0.45	1.07	0.70	-0.09	1.47
Industrial	*-1.25*	*-2.16*	*-0.34*	-0.83	-1.68	0.02
School Density	-0.04	-1.79	1.69	0.06	-1.70	1.80
Activity Center Density	0.28	-0.19	0.75	-0.03	-0.50	0.44
Walking mode share	*3.43*	*1.30*	*5.62*	-0.66	-2.65	1.45
Number of Trips	*0.08*	*0.06*	*0.09*	*-0.02*	*-0.03*	*0.00*
Random effects:						
σ_v	3.08	1.88	4.67	2.45	1.72	3.34
σ_u	1.06	0.53	1.96	2.48	0.93	5.95
Marginal Likelihood	-2418.87			-2421.72		
Spatial Dependence $\frac{\sigma_u}{\sigma_u+\sigma_v}$	31.07%			17.05%		
Significant effects are marked in "*Italic*".						

For road network features, the effects of intersection densities on the pedestrian crash frequency versus the risk vary depending on the types of intersections in this study. With regard to the densities of 4-way intersections and complicated intersections (more than 5-way), it shows positive associations with the pedestrian crash frequency and the risk. The effect of 3-way intersection density remains unclear. The findings of intersections' effects on the pedestrian crash frequency are generally consistent with a prior study was done for Montreal (Ukkusuri et al., 2012). No previous study has examined the effects of different intersections on the pedestrian crash risk. The positive associations between 4-way/5-way intersection and the pedestrian crash risk may due to some unobserved factors, such as motorists' temporal behaviors or pedestrians' traffic violation when crossing streets. In summary, pedestrians are more exposed to collisions and risks at intersections.

Moreover, sidewalk density is negatively correlated with the pedestrian crash frequency and the risk with Seattle's data, which is basically consistent with Wang and Kockelman's finding (2013). This conclusion leads to a policy implication that densifying sidewalks can improve walking environment safety for pedestrians.

The proportion of steep areas is selected to represent the zonal steepness of TAZs. This variable suggests negative associations with the pedestrian crash frequency and the risk. This may be due to that pedestrians are less likely to walk in steep areas by spending more physical efforts and taking a higher risk of falling down.

The density of bus stops is a commonly used variable in modeling pedestrian crash frequency. An agreed finding is that bus stop density is positively associated with pedestrian crash frequency, with no exception of this study (Miranda-Moreno et al., 2011; Ukkusuri et al., 2012; Wang and Kockelman, 2013). Stopped buses may block pedestrians' sights when crossing the streets, and areas with better transit service are expected to have more human activities, associated with more conflict between pedestrians and vehicles. These results indicate that roadway design and bus stop location choice should be carefully considered. Separating barriers should be placed between transit lanes and sidewalks. Bus drivers should slow down when they are stopping, starting, and turning.

In relation to land use, a few studies suggest that pedestrian crash frequency is positively correlated with commercial land use (Miranda-Moreno et al., 2011; Narayanamoorthy et al., 2013; Wier et al., 2009), but this relationship is unclear with Seattle's data. This study shows a negative association between industrial land use and pedestrian crash frequency, which is consistent with Miranda-Moreno et al.'s finding for Montreal (2011), but inconsistent with Ukkusuri et al.'s (2011, 2012) studies for New York. Industrial areas are mostly of the pedestrian unfriendly environment. The likelihood of occurring a pedestrian crash in industrial areas is expected to be rare event due to a low pedestrian volume. The effects of open lands on pedestrian crashes were contradictory in two prior studies (Miranda-Moreno et al., 2011; Ukkusuri et al., 2012), and such an effect is not able to be determined in this study. Land use mixture indicates positive associations with the pedestrian crash frequency and the risk in this research, in contrast with a negative association in Wang and Kockelman's study for Austin, Texas (2013). To summarize, many land use effects appear to be inconsistently correlated with pedestrian crash frequency in the prior research. Possibly the inconsistencies are due to the variations of different urban forms between Montreal, New York, Austin, and Seattle, or due to the built environment variables were quantified at different scales. More studies are expected to be conducted to raise generalizable conclusions, or to confirm the effects of land use on pedestrian crash frequency versus pedestrian crash risk are just case-specific.

Schools and activity centers are trip generators of pedestrian travels, especially for teenagers, while the effects of school density are unclear in this research. The variable, density of activity centers, including churches, public libraries, art centers, environment education centers, playgrounds, neighborhood and community centers, also shows unclear effects with the pedestrian crash frequency and the risk.

Prior research showed that traffic volume was positively associated with pedestrian crash frequency (Miranda-Moreno et al., 2011). Since Seattle only has the traffic volume data on arterials. This study chooses the TAZ-based forecasted number of trips as a substitute to traffic volume. The effect shows a consistent positive relationship between the number of trips and the pedestrian crash frequency with the data for Seattle. However, the number of trips shows a negative association with the pedestrian crash risk in this study, indicating that pedestrians are comparatively safe to walk in areas with a high level of traffic. To explain, pedestrians are more exposed to crashes when there is more on-road traffic. As more cars and pedestrians on the streets, driving speeds are declining, and thus the road environment is becoming safer. Similarly, walking mode share indicates a similar contradictory relationship for the pedestrian crash frequency and the risk. Walking mode share is positively associated with the crash frequency, but negatively correlated with the crash risk. Again, as more pedestrians walking on the streets, the likelihood of occurring a collision is increasing due to the increase of exposure. Simultaneously, the crash risk is decreasing with pedestrians' increase because they are more visible to motorists. Both of these results are reflections of the theory of *safety in numbers*.

Regarding socio-demographic factors, household density shows no significant effect impacting the pedestrian crash frequency versus the risk; while employment density indicates a negative correlation with the pedestrian crash risk. Again, it confirms the theory of *safety in numbers* that walking is safer in dense employment centers.

5. Conclusions and Limitations

This study presents two TAZ-based ICAR models for pedestrian crash frequency versus risk for Seattle, and various aggregated factors of road network, land use, socio-demographic, and travel demand are investigated. The results show that spatial autocorrelations are insignificant in the two models. The rest variability is mostly explained by unobserved heterogeneities.

To conclude, intersection areas have more pedestrian crashes and higher risks because both motorists and pedestrians are more exposed to collisions. However, it is not reasonable to reduce the number of intersections, because intersection areas are the right places where pedestrians and motorists interact with each other. Reducing intersections will result in more speeding, less walking, and a greater probability of pedestrian's traffic violations at midblock. Building footbridges or underpass at risk intersections are the other effective ways to reduce pedestrian crashes. Additionally, the total number of trips show a contradictory relationship with the pedestrian crash frequency and the risk. In particular, bus stop density and land use mixture are positive predictors, while sidewalk density and zonal steepness are negative predictors of the pedestrian crash frequency and the risk.

This rich data set allows us to draw important policy implications. Findings on the factors of road network and land use are generally consistent between the two models, while inconsistencies are shown in the estimates for travel demand characteristics and socio-demographic factors. To make it brief, the policy recommendations drawn for local authorities and transport engineers are: (1) densifying sidewalks can improve pedestrian safety; (2) optimally isolating pedestrians and automobile traffic at intersection areas, especially those zones with more bus stops; (3) assigning specific safety treatments to areas with multiple land use purposes; and (4) advocating for walking conditional on the availability of well-planned facilities. Pedestrian crashes are more likely to occur in activity centers, which are characterized as more mixed land use and better street connectivity. It indicates that land use, roadway design, and road safety management are jointly impacting the success of a walkable environment.

Urban design principles adopted from the new urbanism and smart growth encourage applying the compact development to build sustainable cities, also called density, diversity, and design (Cervero and Kockelman, 1997). These planning strategies contribute to the growth in the number of pedestrians. However, this research suggests that greater street connectivity and more mixed land use are associated with more pedestrian crashes and higher collision risks, which are contradictory to these principles. The exposure to crashes is increasing along with the number of on-road pedestrians. Yet, according to the aforementioned findings, planners and engineers cannot blindly abandon those strategies for such induced pedestrian crashes and risks. Instead, they should include pedestrian safety as a primary concern in practice as essential urban design principles.

Regarding limitations of this research, a weakness is that the crash data covers a 5-year period. The built environment features can be modified after crashes have occurred. In such a long time, the temporal effect of built environment changes cannot be accurately tracked, and the results can be possibly reported with biases. Secondly, underreporting of pedestrian crashes is more likely to happen in suburban areas and local streets, especially for crashes of slight injuries. In this context, the dependent variable can be biasedly reported. Thirdly, the geocoded crash sites are snapped to the closest geometrical road centers or intersections in the ArcGIS, which are no longer representing their original places. TAZs are mostly split by main arterials, and a crash may just fall into the cross-boundary between two neighboring TAZs due to minor geocoding errors. Accuracy improvements in geocoding and reporting are expected to improve the preciseness of quantified built environment factors and the counted number of crashes. Fourthly, a forecasted number of walking trips may not be the most appropriate exposure variable to measure pedestrian crash risk. It cannot represent the real number of on road pedestrians because its prediction is greatly based on origins and destinations. Better pedestrian counters should be developed to record and forecast more accurate pedestrian volume data.

Future work could involve testing the inconsistencies shown in the effects of land use factors, controlling the possible bias due to the temporal variations in the built environment and different geospatial units, reporting crash geographical coordinates with improved accuracy, and recording more precise pedestrian volume data for better safety research.

Note

1. LUM: land use mixture or the degrees of mixing land use, which is measured by

$$LUM=((-1)/\ln n)*(\sum Pi *\ln Pi)$$

Where *n* is the number of different land use type classes in the TAZ and *Pi* is the proportion of land in type *i* in the TAZ. This index is calculated separately for each TAZ. The resulting variable LUM is the land use mix entropy index, which varies from 0 (homogeneous land use) to 1 (most mixed land use).

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