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The effect of road network patterns on pedestrian safety: A zone-based Bayesian spatial modeling approach

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ABSTRACT

Pedestrian safety is increasingly recognized as a major public health concern. Extensive safety studies have been conducted to examine the influence of multiple variables on the occurrence of pedestrian-vehicle crashes. However, the explicit relationship between pedestrian safety and road network characteristics remains unknown. This study particularly focused on the role of different road network patterns on the occurrence of crashes involving pedestrians. A global integration index via space syntax was introduced to quantify the topological structures of road networks. The Bayesian Poisson-lognormal (PLN) models with conditional autoregressive (CAR) prior were then developed via three different proximity structures: contiguity, geometry-centroid distance, and road network connectivity. The models were also compared with the PLN counterpart without spatial correlation effects. The analysis was based on a comprehensive crash dataset from 131 selected traffic analysis zones in Hong Kong.

The results indicated that higher global integration was associated with more pedestrian-vehicle crashes; the irregular pattern network was proved to be safest in terms of pedestrian crash occurrences, whereas the grid pattern was the least safe; the CAR model with a neighborhood structure based on road network connectivity was found to outperform in model goodness-of-fit, implying the importance of accurately accounting for spatial correlation when modeling spatially aggregated crash data.

1. Introduction

As a means of primary transportation, walking holds promise for not only supporting public health, but also reducing resource and land consumption, air and noise pollution, and greenhouse gas emissions (Gomez-Ibanez et al., 2009; Ewing et al., 2011). However, walking is also associated with negative public health outcomes related with pedestrian–vehicle crashes. Approximately 400,000 pedestrians are killed in pedestrian–vehicle crashes each year worldwide (Naci et al., 2009), whereas in Hong Kong, pedestrians accounted for more than half of the road traffic fatalities (HKTD, 2014), a proportion that was much higher than that in other high-income countries (e.g., the United States, the United Kingdom, and Japan). Hence, effective road safety strategies must be formulated and implemented to improve the safety of these vulnerable road users (Wong et al., 2002; Loo et al., 2005, 2007).

Over the past decade, numerous studies have been conducted to identify the effects of potential contributing factors, such as pedestrian and driver characteristics (e.g., age and gender), road geometric features (e.g., road width, horizontal and vertical alignment), traffic characteristics (e.g., traffic volume and travel speed), neighborhood environmental conditions (e.g., urban form, land use, and access to public transport) and other factors (e.g., weather, temporal, and lighting), on the occurrence of crashes involving pedestrians (Gårder, 2004; Lee and Abdel-Aty, 2005; Kim et al., 2008; Wier et al., 2009; Ewing and Dumbaugh, 2009; Moudon et al., 2011; Siddiqui et al., 2012, 2014; Lam et al., 2014; Yao et al., 2015; Wang et al., 2016).

In addition to the preceding contributing factors, road network structures have been identified as important in determining traffic safety, especially for pedestrians (Marshall and Garrick, 2010b; Rifaat et al., 2011, 2012; Wei and Lovegrove, 2012; Dumbaugh and Zhang, 2013; Zhang et al., 2015). Urban road networks not only influence quality of life, but also promote economic development and regional growth (Florida, 2002) and improve people's physi-

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cal fitness and health (Frank et al., 2003). According to Appleyard (1980), an ideal road network should possess several characteristics (such as located in a livable environment, located in neighborly territory, and being green and pleasant) in addition to acting as thoroughfares for carrying people and goods from one place to another. A reduction in pedestrian crashes is one of the road and traffic-related issues that has an effect on neighborhood life. The structure of road networks influences pedestrian safety through its effects on the fundamental characteristics of traffic volumes and journey patterns for both vehicles and pedestrians (Zhang et al., 2015). Road network patterns also affect travel activities, vehicle speeds, and driver behavior, thus influencing road safety (Quddus, 2008).

Previous studies have considered road network structures in different ways. One common way of classifying road network patterns is based on the concept of macro- and micro-level road networks proposed by Marshall (2004). Macro-level or citywide road networks distinguish roads that are typically continuous over a substantial part of the city and enable travel from one part of the city to another. In contrast, micro-level or neighborhood road networks mainly serve residential neighborhood travel, as these roads are on routes that are not continuous over a significant part of the city. Following Marshall and Garrick (2010a, 2010b, 2011), four types of citywide road network (linear, tributary, radial, and grid) and two types of neighborhood road network (tree and grid) are defined and combined to describe hierarchical road network patterns. An alternative method involves concentrating directly on the overall road network patterns of a community rather than the different types of road network pattern and then combining the different types to compose a new type. For instance, Lovegrove and Sun (2010, 2013) classified road network patterns into five categories: fused grid, commonly used grid, cul-de-sac, three-way offset, and Dutch sustainable road safety (SRS). They found that fused grid and three-way offset patterns were safer than grid, cul-de-sac, and Dutch SRS patterns. Southworth and Ben-Joseph (2003) classified road network patterns into five other categories: gridiron, fragmented parallel, warped parallel, loops and lollipops, and lollipops on a stick. Rifaat et al. (2010, 2011, 2012) further merged fragmented parallel patterns and lollipops into a mixed pattern and concluded that relative to limited access patterns, the grid pattern was associated with more crashes and lower pedestrian crash severity.

The main limitation of the preceding studies is that their road network classification methods were largely based on the visual inspections and hence may be prone to subjectivity and uncertainty due to the unavailability of quantitative road network indices. Moreover, these manual classification approaches are time-consuming, limiting their generalization to large study regions. To overcome these problems, some researchers have attempted to extract the structures of road networks quantitatively based on topological measurements (Wang et al., 2012, 2013; Zhang et al., 2012, 2015).

This study introduced an alternative innovative road network modeling technique known as space syntax (Hillier and Hanson, 1984; Hillier, 1996) to quantify the characteristics of different road network patterns. The notion of syntax refers to relationships between different spaces, or interactions between spaces and society. It recognizes that spatial patterns or structures greatly influence human activities and behavior in urban environments. Typical applications of space syntax include pedestrian and bicyclist modeling, criminal mapping, pollution analysis, and retail viability modeling (Jiang, 1999; Ratti, 2004). Space syntax can objectively measure the effects of road network patterns on accessibility (Raford et al., 2007). This study therefore used space syntax to quantify the structures of road network patterns.

To determine the effects of road network patterns on pedestrian safety, aggregate relationships between the aforementioned independent variables and pedestrian crash counts can be established using macro-level or area-wide safety performance functions (SPFs). Traditional Poisson and Poisson-lognormal (PLN) models ignore the issue of spatial correlation, which may lead to biased parameters and incorrect inferences (Huang and Abdel-Aty, 2010). To address the spatial dependence between adjacent zones, Bayesian spatial models with a conditional autoregressive (CAR) prior have been widely applied in current road safety analysis (Quddus, 2008; Mitra, 2009; Aguero-Valverde and Jovanis, 2008, 2010; Siddiqui et al., 2012; Wang et al., 2012, 2013; Xu et al., 2014, 2017; Xu and Huang, 2015).

Within the framework of CAR, the spatial relationship is typically linked by virtue of a spatial weight matrix. One commonly used weighting scheme includes adjacency-based first-order neighbors (Miaou et al., 2003; Aguero-Valverde and Jovanis, 2008; Quddus, 2008), which can be defined as all of the observation units that connect directly with the one in question. Additional consideration is given to distance decay-based forms (Aguero-Valverde and Jovanis, 2010; Dong et al., 2014; Wang et al., 2016). However, the pure geographical proximity may be inadequate to express the spatial relationships under investigation. In reality, a more rational spatial weighting configuration is required to simultaneously consider the geographical dimension and other aspects (e.g., travel frequency, travel modes, and travel demand) that vary with the context of study. For this purpose, this study proposed a new neighborhood structure using road network connectivity to reflect the potential traffic interactions between adjacent zones.

Overall, this study described an innovative street pattern modeling technique known as space syntax to objectively quantify the structure of road networks. More specifically, the primary objective of this study was to explore how road network characteristics—in terms of global integration—are associated with zone-level pedestrian safety using both non-spatial (e.g., PLN model) and spatial (e.g., CAR model) SPFs. Another objective was to compare different spatial proximity structures at the traffic analysis zone (TAZ) level. Bayesian spatial models with a CAR prior were used with three different types of neighborhood structure: contiguity, geometry-centroid distance, and road network connectivity.

The remainder of this paper is structured as follows. Section 2 describes the data collection process. Section 3 presents the structures of non-spatial and spatial SPFs. Section 4 summarizes the results and discusses the investigation. Section 5 presents the conclusions and suggestions for the future direction of research.

2. Data

A comprehensive database relating to pedestrian–vehicle crashes and traffic-related variables for Hong Kong was established using geographical information system (GIS) techniques.

The spatial units for analysis were the TAZs from the Hong Kong Planning Vision and Strategy (PVS) zoning system, which is managed by the Hong Kong Planning Department. The PVS zoning system divides the whole of Hong Kong into different sectors and is revised every few years to better describe the zoning boundary. The PVS 338 zoning system uses a 2001-based Territorial Population and Employment Data Matrix (TPEDM). There are 338 TAZs in this zoning system. Of these, 131 TAZs (38.76%) were finally selected as having adequate traffic and geometric information. To examine the role of road network patterns and zone-related variables that contribute to pedestrian safety at a more disaggregated level, the database was organized into 4-h periods: 07:00–11:00 (morning), 11:00–15:00 (noon), 15:00–19:00 (afternoon), 19:00–23:00