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Influence of built environment on pedestrian crashes: A network-based GIS analysis

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A R T I C L E I N F O

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A B S T R A C T

Built environment is an essential component of traffic safety. Using data from the Georgia Department of Transportation from 2000 to 2007, the authors investigated the influence of built environment on pedestrian crashes in DeKalb County, Georgia, United States. A network-based kernel density technique was used to locate the hotspots of pedestrian crashes. An environmental audit was then conducted to provide a qualitative assessment of the built environment within each hotspot. Bivariate analysis and negative binomial models were utilized to examine the influence quantitatively after the road was partitioned into short road segments. Results show more pedestrian crashes were likely to occur on segments with less gradient change and with more public transit stops, and be close to census tracts with more public transit users, fewer seniors, and more linguistically isolated households. The findings emphasize the need for more extensive prevention campaigns around the hotspots and consideration of pedestrian safety in future urban and environmental planning.

1. Introduction

Pedestrian crashes remain a costly burden in the United States. There were on average over 4500 pedestrians killed and an estimated 66,000 injured per year from 2004 to 2013 according to the National Highway Traffic Safety Administration (National Center for Statistics and Analysis, 2015). These crashes are associated with tremendous economic and health costs. The estimated comprehensive cost of pedestrian crashes is $65 billion in 2014 (National Highway Traffic Safety Administration, 2016). Furthermore, the literature show substantial health burdens resulted from traffic injuries (Chalabi, Roberts, Edwards, & Dowie, 2008; DiMaggio & Li, 2011).

Built environment, which offers an opportunity for physical activities, may become hazards for pedestrians negotiating traffic. From the perspective of traffic safety, built environment refers to road designs, infrastructure, surrounding establishments, and land-use types, among others (Chen, 2015; Clifton, Burnier, & Akar, 2009). Road design, for example, may reduce pedestrian risks via marked and signalized crosswalks, raised medians, or pedestrian refuge islands (Miranda-Moreno, Morency, & El-Geneidy, 2011; Ukkusuri, Miranda-Moreno, Ramakrishna, & Isa-Tavarez, 2012). These studies showed that surroundings providing heavy pedestrian traffic (e.g., grocery stores or restaurants) along highway corridors may increase the risk of pedestrian-vehicle collisions and the injury severity. However, the relative importance of each built-environment feature in affecting the risk of pedestrian crashes remains unclear. In this article, we examine the role of various built-environment characteristics in pedestrian crashes. Geographic Information Systems (GIS) and network-based geospatial methods were used to create detailed measures of built-environment characteristics, and their influence on pedestrian crashes was assessed using qualitative and quantitative approaches.

Recognizing the tremendous health and economic burdens, previous studies have examined built environment as exemplified by its profound influence. Studies consistently show that surrounding population or establishments (e.g., alcohol outlet density, business access, or transit access) served as critical indicators influencing the likelihood of pedestrian crashes (Kuhlmann, Brett, Thomas, & Sain, 2009; Schuurman, Cinnamon, Crooks, & Hameed, 2009). Yet Clifton and Kreamer-Fults (2007) argued that these areas were associated with increased pedestrian traffic, and instead road design may play a more important role. Some studies suggested that road design affected drivers' behaviors (Ben-Bassat & Shinar, 2011; Rengarasu, Hagiwara, & Hirasawa, 2009). As non-

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behavior determinants of crash risks, examining the built environment especially in areas where pedestrian crashes frequently occur is valuable to build a safer environment (Haynes et al., 2008; Miranda-Moreno et al., 2011).

Road design has been recognized as an important built environment factor for drivers' performance, yet more research concerning its influence on pedestrian safety are still necessary. Previous studies suggested that road geometry influenced driving behaviors. Horizontal curves, for example, may affect drivers' attention and ability to anticipate the course of the road ahead (Arien et al., 2013; Ben-Bassat & Shinar, 2011). The increase of curve radius was reported to be associated with decreased crash rates and thus might offer protection (Charlton, 2007; Jones et al., 2008). But these studies used either lab-based simulations in controlled environments or rural highways. Besides, they focused on vehicle-only traffic incidents. Little has been done to assess the impact of road design on pedestrian safety in urban areas where 73% of pedestrian fatalities occurred (National Center for Statistics and Analysis, 2015).

While the importance of built environment concerning pedestrian safety is no question, the assessment of the built environment is challenging given the unique nature of network-constrained crashes. This feature requires spatial analysis to account for linear distribution and the fundamental spatial uncertainties inherited from it. Some studies analyzed crashes at a point level (e.g., Eckley & Curtin, 2013; Li, Zhu, & Sui, 2007). This approach is valuable to identify crash clusters, that is, to locate where the problems are. The point-level analysis encounters a mismatch problem in scale, i.e., ecological fallacy, when built environment is quantified as area-based measures, such as population density or alcohol outlet density (e.g., Clifton & Kreamer-Fults, 2007; Ukkusuri et al., 2012). Furthermore, the real position of a crash is uncertain because there would be a distance from the point of impact to where a vehicle and involved pedestrians are finally located, and therefore a hazardous site should be more of a road segment than a point (Bil, Andrasik, & Janoska, 2013).

To mitigate this challenge, some studies aggregated crashes into areal units such as traffic analysis zones (e.g., Chen, 2015; Haynes, Jones, Kennedy, Harvey, & Jewell, 2007). This approach makes it convenient to quantify built environment, for example, the number of alcohol outlets in a census tract. This treatment, however, becomes an issue because units of analysis (e.g., traffic analysis zones or census tracts) cover broad areas where built environment features are heterogeneous (Li et al., 2007). Crashes and built environment mismatch even though they are in the same units. The mismatch may attribute to mixed research results because different levels of aggregation may produce different findings (Nunn & Newby, 2015). This challenge can be lessened by using the possibly smallest area units and different scales of spatial aggregation (Paez & Scott, 2004). Recent years have seen the advancement of GIS to operationalize some network-based quantitative measures. Drilling down to individual incident clusters in specific segments on a road network, therefore, is vital to investigate built-environment impact.

Recent studies have introduced some network-based clustering techniques to identify hotspots of traffic incidents. Hotspots are zones on a road where crashes highly concentrate (Kuo, Zeng, & Lord, 2011; Yamada & Thill, 2010; Young & Park, 2014). Various network variant methods have been proposed to identify hotspots, for example, the network-based kernel density estimation methods (NKDE; Okabe, Satoh, & Sugihara, 2009; Xie & Yan, 2008). Describing the need to examine clustering strengths, some researchers introduced statistical tests to assess clustering significance, such as local indicators of network-constrained clusters (Nie, Wang, Du, Ren, & Tian, 2015; Yamada & Thill, 2010) or dangerousness index (Steenberghen, Aerts, & Thomas, 2010). Bil et al. (2013) argued that these methods often require the consideration of traffic flow (e.g., annual average daily traffic), yet the relationship between traffic flow and incidents is often complicated and non-linear. The authors proposed to run NKDE on sections between two intersections to mitigate the issue of varying traffic flow on streets and used Monte Carlo tests to evaluate the significance of the density (Bil et al., 2013). These statistical tests, however, become impractical to pedestrian-vehicle collisions. The reason stems from the fact that the number of pedestrian crashes depends on not only the intensity of both vehicles and pedestrians but also their interactions. This turns to be more challenging given the difficulty and unreliability of pedestrian counting. Although NKDE might not be as statistically sophisticated as the other methods, it is advantageous because of its simplicity and its expression of the uncertainty about the exact crash locations using a kernel bandwidth (Bil et al., 2013). Some studies (de Andrade et al., 2014; Schuurman et al., 2009) used KDE followed by a built-environment audit to identify environmental factors. Their use of the planar KDE, however, raises an issue because of its limitation in analyzing the network-constrained traffic incidents (Lu & Chen, 2007; Yamada & Thill, 2004).

Given the paucity of research to consider the linear nature of pedestrian crashes when examining environmental factors, the primary objective of this paper is to conduct a network-based spatial analysis to identify road segments of crash hotspots, and assess the built environment using mixed methods (Creswell, 2014; Harden & Thomas, 2010). We hypothesize that built environment plays an important role in some road segments experiencing frequent pedestrian crashes. We first used the NKDE to locate hotspots that have the highest densities of pedestrian crashes. An environmental audit was conducted to examine the built environment in each hotspot. We then used a network-based technique to partition the road into short road segments, based on which we evaluated built environment using bivariate and negative binomial tests. The advantage of using mixed methods is twofold. First, the environmental audit provides qualitative measures gathered via field-based observations that are often unavailable in secondary datasets. Second, the quantitative analysis validates and generalizes the qualitative findings by statistical tests on all crashes regardless of the hotspots. The two methods complement each other, thus providing in breadth and depth of a more comprehensive understanding of the built environment than either qualitative or quantitative approaches alone. This research contributes to the literature by taking advantage of the linear nature of crashes while examining the built environment. The segments identified with the highest densities of pedestrian crashes provide areas of focus for city planning and transportation authorities to develop prevention strategies. In addition, the findings may be used to locate areas for studying road users' behaviors.

2. Material and methods

The study area is in DeKalb County, one of the five core counties in metropolitan Atlanta, Georgia, United States (Fig. 1). Unlike the other four mostly automobile dependent counties with large stretches of suburbs and rural farmlands, DeKalb County is a predominately urban county as evidenced by its population density (Fig. 1). It has a population of nearly 700 thousand residents and has the highest population density in Georgia. Most areas in DeKalb have sidewalks and public transits available. Besides, DeKalb has apparent elevation change, which provides an opportunity for understanding how road characteristics, such as geometry, affect pedestrian crashes.

Pedestrian-vehicle collision records were obtained from the