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Bayesian approach to model pedestrian crashes at signalized intersections with measurement errors in exposure

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ABSTRACT

This study intended to identify the potential factors contributing to the occurrence of pedestrian crashes at signalized intersections in a densely populated city, based on a comprehensive dataset of 898 pedestrian crashes at 262 signalized intersections during 2010–2012 in Hong Kong. The detailed geometric design, traffic characteristics, signal control, built environment, along with the vehicle and pedestrian volumes were elaborately collected. A Bayesian measurement errors model was introduced as an alternative method to explicitly account for the uncertainties in volume data. To highlight the role played by exposure, models with and without pedestrian volume were estimated and compared. The results indicated that the omission of pedestrian volume in pedestrian crash frequency models would lead to reduced goodness-of-fit, biased parameter estimates, and incorrect inferences. Our empirical analysis demonstrated the existence of moderate uncertainties in pedestrian and vehicle volumes. Six variables were found to have a significant association with the number of pedestrian crashes at signalized intersections. The number of crossing pedestrians, the number of passing vehicles, the presence of curb parking, and the presence of ground-floor shops were positively related with pedestrian crash frequency, whereas the presence of playgrounds near intersections had a negative effect on pedestrian crash occurrences. Specifically, the presence of exclusive pedestrian signals for all crosswalks was found to significantly reduce the risk of pedestrian crashes by 43%. The present study is expected to shed more light on a deeper understanding of the environmental determinants of pedestrian crashes.

1. Introduction

Pedestrian safety continues to be a considerable public health concern worldwide (Naci et al., 2009; Zegeer and Bushell, 2012; Stoker et al., 2015). Although pedestrian casualties due to traffic crashes in Hong Kong have dropped by 19.3% over the past decade, approximately 3500 pedestrians are still injured each year (Hong Kong Transport Department (HKTD, 2017). Pedestrians also accounted for more than half of the road traffic fatalities, a proportion much higher than that in other high-income areas. To improve the safety of these vulnerable road users, effective interventions are urgently required to be formulated and implemented.

With the rapid progress of urbanization, a growing number of intersections in cities are controlled by traffic signals. The inadequate accommodation of pedestrians' needs makes them difficult to cross streets and increases the number of pedestrian injuries (Xu et al., 2016). In 2016, about 1200 pedestrian injuries occurred at intersections in Hong Kong, among which 50% were under signal control (Hong Kong Transport Department (HKTD, 2017). A better understanding of factors contributing to pedestrian crashes at signalized intersections is therefore imperative if walking is advocated as a safe and attractive travel mode. Such information can also facilitate safety planners and policy makers in the design of appropriate infrastructures to improve pedestrian mobility and safety.

In the past two decades, researchers have attempted to develop different predictive models to explore the effects of different types of factors on pedestrian crash counts. Existing studies have focused primarily on the area-wide level (LaScala et al., 2000; Graham and Glaister, 2003; Noland and Quddus, 2004; Morency and Cloutier, 2006; Wedagama et al., 2006; Loukaitou-Sideris et al., 2007; Dissanayake et al., 2009; Kuhlmann et al., 2009; Wier et al., 2009; Chakravarthy et al., 2010; Cottrill and Thakuriah, 2010; Ha and Thill, 2011; Delmelle et al., 2012; Rifaat et al., 2012; Ukkusuri et al., 2011, 2012; Siddqui et al., 2012; Dumbaugh and Zhang, 2013; Graham and McCoy, 2013;

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Noland et al., 2013; Wang and Kockelman, 2013; Jermprapai and Srinivasan, 2014; Steinbach et al., 2014; DiMaggio, 2015; Lee et al., 2015a, 2015b; Yao et al., 2015; Yu, 2015; Cai et al., 2016, 2017; Chen and Zhou, 2016; Wang et al., 2016; Guo et al., 2017; Osama and Sayed, 2017; Tasic et al., 2017; Xie et al., 2017; Ding et al., 2018; Goel et al., 2018). Relatively little research effort has been devoted to investigating the relationship between the number of motor vehicle–pedestrian crashes and potential risk factors at intersections (See: Table A1 in Appendix; Leden, 2002; Lyon and Persaud, 2002; Lee and Abdel-Aty, 2005; Geyer et al., 2006; Schneider et al., 2010; Torbic et al., 2010; Miranda-Moreno et al., 2011; Pulugurtha and Sambhara, 2011; Elvik et al., 2013, 2016; Strauss et al., 2014; Quistberg et al., 2015a, 2015b; Kröyer, 2016; Mooney et al., 2016; Lee et al., 2017; Thomas et al., 2017; Wang et al., 2017), particularly at signalized intersections in a densely populated city (Leden, 2002; Lyon and Persaud, 2002; Torbic et al., 2010; Pulugurtha and Sambhara, 2011; Miranda-Moreno et al., 2011; Strauss et al., 2014).

Not surprisingly, with the increase in vehicle and pedestrian volumes, the absolute number of pedestrian crashes also increases. A nonlinear relationship has consistently been reported, indicating that as the number of pedestrians increases, the crash risk for each individual pedestrian decreases (Leden, 2002; Lyon and Persaud, 2002; Geyer et al., 2006; Schneider et al., 2010; Torbic et al., 2010; Miranda-Moreno et al., 2011; Elvik et al., 2013; Strauss et al., 2014; Elvik, 2016; Kröyer, 2016; Mooney et al., 2016). This is referred to as “safety in numbers” effects (Jacobsen, 2003; Elvik and Bjørnskau, 2017; Xu et al., 2017b). Although pedestrian volume is crucial in determining pedestrian crash occurrences, few transportation agencies regularly collect these data on a large scale due to limited resources. The number of pedestrians is thus mostly estimated based on a short period of field observations (Leden, 2002; Lyon and Persaud, 2002; Schneider et al., 2010; Torbic et al., 2010; Miranda-Moreno et al., 2011; Pulugurtha and Sambhara, 2011; Elvik et al., 2013, 2016; Strauss et al., 2014; Quistberg et al., 2015b; Kröyer, 2016; Mooney et al., 2016), predicted by pedestrian activity models such as Space Syntax (Geyer et al., 2006) and “Ballpark” method (Thomas et al., 2017), or surrogated as surrounding land use and demographic characteristics (Quistberg et al., 2015a; Lee et al., 2017; Wang et al., 2017). It is noteworthy that either absence or improper representation of pedestrian exposure probably leads to inconsistent results (Steinbach et al., 2014). The measurement errors induced in this process may also bias the parameter estimates (Kröyer, 2016).

In addition to the vehicle and pedestrian volumes, geometric design, such as the number of approaches (Miranda-Moreno et al., 2011; Pulugurtha and Sambhara, 2011; Quistberg et al., 2015a; Lee et al., 2017; Thomas et al., 2017), the number of lanes (Thomas et al., 2017), the number of right-turn-only lanes (Schneider et al., 2010), the maximum number of lanes crossed by pedestrians (Torbic et al., 2010), lane width (Quistberg et al., 2015a), average slope of terrain (Thomas et al., 2017), the presence of raised medians (Schneider et al., 2010), the presence of one-way streets (Quistberg et al., 2015a), the presence of sidewalks (Quistberg et al., 2015b), the presence of pedestrian barriers (Quistberg et al., 2015b), the presence of marked crosswalks (Mooney et al., 2016), and the presence of on-street parking (Quistberg et al., 2015b; Thomas et al., 2017) were found to be closely related to the frequency of pedestrian crashes at intersections. The presence of specific facilities close to intersections, i.e., bus stops (Torbic et al., 2010; Miranda-Moreno et al., 2011; Mooney et al., 2016; Thomas et al., 2017), transit stops (Pulugurtha and Sambhara, 2011), schools (Miranda-Moreno et al., 2011), street vendors (Quistberg et al., 2015b), alcohol sales establishments (Torbic et al., 2010), and billboards (Mooney et al., 2016), was reported to significantly increase pedestrian crashes. Intersections located in neighborhoods with commercial land use (Geyer et al., 2006; Schneider et al., 2010; Torbic et al., 2010; Miranda-Moreno et al., 2011; Thomas et al., 2017), lower income levels (Torbic et al., 2010; Thomas et al., 2017), denser population (Quistberg et al., 2015a; Lee et al., 2017; Wang et al., 2017), higher employment rates (Quistberg et al., 2015a), and a higher proportion of residents under 18 years old (Schneider et al., 2010) were also associated with more pedestrian crashes. However, relative to the geometric and built environment factors, there is potential for further insights regarding the effects of signal timing, although they are usually designed according to the intersection geometry and traffic volume.

Relationships between the aforementioned explanatory variables and pedestrian crash counts can be established using crash prediction models. Traditional Poisson and negative binomial models have a strong assumption that their observations should be mutually independent. This fundamental hypothesis is almost always violated (Mannering and Bhat, 2014). More advanced models, such as the conditional autoregressive (Xu et al., 2014; Guo et al., 2017; Goel et al., 2018; Cai et al., 2018a), random parameters (Anastasopoulos and Mannering, 2009; Hou et al., 2018), geographically weighted regression (Xu and Huang, 2015; Gomes et al., 2017; Cai et al., 2018b), spatially varying coefficients (Xu et al., 2017a), and spatiotemporal mixture models (Cheng et al., 2018) have therefore been introduced to achieve more accurate and reliable estimations. In particular, El-Basyouny and Sayed (2010) proposed an approach to address the measurement errors in traffic volume when modeling freeway crash counts. Their results suggested that the adjustment of measurement errors in traffic volume could significantly improve model performance and result in unbiased inferences.

Based on a comprehensive dataset of 898 pedestrian crashes at 262 signalized intersections over a 3-year period in Hong Kong, this study intends to quantify the effects of various factors, including the geometric design, traffic characteristics, signal controls, and built environment characteristics, on the frequency of motor vehicle–pedestrian crashes at signalized intersections in a densely populated city. A novel Bayesian measurement errors model is elaborately developed to accommodate the uncertainties in vehicle and pedestrian volumes. To illustrate the role played by exposure, the estimated coefficients of models with and without pedestrian volume are presented and compared. The present study is expected to shed more light on a deeper understanding of the environmental determinants of pedestrian crashes.

2. Data

We sampled the intersections based on a comprehensive set of traffic impact assessment reports for the years 2011 and 2012. As the traffic impact assessment was conducted for planning and design purposes and did not investigate the crash records in advance, we assumed no systemic biases in this sampling process. A total of 262 signalized intersections (77 on Hong Kong island, 130 in Kowloon and 55 in New Territories) with adequate traffic and geometric information were available for analysis, which accounted for 15.8% of all signalized intersections in Hong Kong.

We obtained the crash data from the Traffic Road Accident Database System, which is maintained by the Hong Kong Transport Department and the Hong Kong Police Force. These data were collected by the police officers at the crash scenes. Only crashes resulting in injuries were recorded in the database. In Hong Kong, crashes occurring within 70 m of the centerline of an intersection were defined by the police as the intersection crashes. In total, 898 motor vehicle–pedestrian crashes were reported at the selected intersections from 2010 to 2012.

The vehicle volume was estimated based on the peak-hour vehicle flows obtained from the Base District Traffic (BDT) models and the 24-hour vehicle traffic profiles at the counting stations reported in the Annual Traffic Census (ATC). The BDT models were developed by the Hong Kong Transport Department for traffic impact assessments and provided peak-hour traffic flow data. The good coverage of ATC counting stations allowed each intersection to be spatially mapped to the nearest ATC counting station. The proportion of peak-hour traffic extracted from the ATC served as a scaling factor, together with the