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Analysis of safety factors for urban expressways considering the effect of congestion in Shanghai, China

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ABSTRACT

Urban expressways are the key components of the urban traffic network. The traffic safety situation on expressways directly influences the efficiency of the whole network. A total of 48,325 crashes were recorded by Shanghai Expressway Surveillance System in a three-year period. Considering the different crash mechanisms under different congestion levels, models for the total crashes, non-congested-flow crashes and congested-flow crashes were respectively formulated based on the real-time traffic condition corresponding to each crash. Moreover, considering the potential spatial correlation among segments, the adjacent-correlated spatial and distance-correlated spatial models were formulated and compared to the traditional non-spatial-correlated model. A Bayesian approach was employed to estimate the parameters. The results showed that the congestion index, merging ratio, ramp density, and average daily traffic significantly affect the crash frequency. The safety factors in non-congested flow and congested flow are different; diverging behavior is more risky in non-congested flow, more lanes tend to increase the risk of crashes in congested flow, and horizontal curves tend to decrease the crash risk in congested flow but cause high risk in non-congested flow. In addition, the distance-correlated spatial model is found to be the best-fitting model. The results of this study suggested that dedicated safety countermeasures can be designed for different traffic situations on urban expressways.

1. Introduction

The urban expressway system is the key component of the urban roadway network, which facilitates a large amount of motorized travel daily. Therefore, the efficiency of the entire roadway network could be seriously influenced by the operation status of the expressways. Meanwhile, according to the data collected by the Shanghai Expressway Surveillance System (SEES), from 2011 to 2013, more than 80 crashes occurred every day in the entire expressway system of Shanghai, and the average crash frequency per million vehicles per kilometer was 4.83. Frequent congestion and delays are caused by crashes. Therefore, to maintain safe and efficient traffic operation on urban expressways, it is particularly important to understand the safety risk factors for urban expressways.

Recurring congestion is another main hazard on the urban expressway system due to the high traffic demand and the limited network capacity. While many previous papers have studied the effects of roadway geometric characteristics on safety, few studies have discussed the relationship between congestion and crashes. Existing research studies have considered several proxies for congestion such as volume over capacity ratio (V/C) and congestion index (CI) (Shefer, 1994; Wang et al., 2009). Noland and Quddus (2005) and Wang et al. (2009) have respectively investigated the safety factors during fixed peak and off-peak periods. However, there is no generally accepted conclusion about the effects of congestion on crashes. Moreover, no previous studies have been conducted on the differences in safety factors under non-congested and congested flow based on the real-time traffic flow data.

Based on the expressway information system in Shanghai, a mass of crash data, along with the real-time traffic flow data, was used in this study. A total of 48,325 crashes (16,564 in non-congested flow and 31,761 in congested flow) were collected over a three-year period. The aim of this paper is to explore the safety factors for urban expressways and to understand the similarities and

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differences of the safety factors in congested and non-congested situations. Considering that the spatial effects may exists, two spatial models and a traditional non-spatial-correlated model were compared using a Bayesian approach. Additionally, models for the total crashes, non-congested-flow crashes and congested-flow crashes were formulated. Both geometric and traffic flow data were collected and considered in these models.

2. Literature reviews

In the previous safety research studies, different types of transportation facilities have been investigated including multi-lane highways, arterials, access roads, and intersections. Because this study focuses on urban expressways, the review will focus on the studies on freeways or urban expressways.

In terms of the methodology, Poisson models are used in the early stage (Miaou and Lum, 1993). However, because the variance of crash data is sometimes significantly greater than the mean, Poisson models may meet the problem of over-dispersion and lead to erroneous estimations. Therefore, Poisson-gamma (also known as negative binomial) models have been applied in many studies (Shankar et al., 1995; Malyshkina and Mannering, 2010; Gomes, 2013). By including gamma-distributed random effects in the Poisson model, the over-dispersion of crash data is adapted in a negative binomial model.

However, such conventional models fail to capture the spatial correlation among the roadway segments, which may lead to an inappropriate estimation. As a result, models considering spatial effects were developed in recent studies. Li et al. (2007) used a conditional autoregressive (CAR) model to eliminate the high uncertainty in the analysis of the relative risk of motor vehicle crashes. Miaou and Song (2005) found that spatial effects correlated to distance can significantly improve the overall model goodness-of-fit. By including joint-distribution random effects through correlated segments, the spatial patterns or clusters were reflected. Thus, a more credible result can be generated.

The Bayesian approach has become popular in recent decades. Compared to the maximum likelihood estimation approach, the Bayesian approach can handle very complex models, especially while the models' likelihood functions are difficult to calculate (Lord and Mannering, 2010). Therefore, it has been widely used in safety studies (Mitra and Washington, 2007; Aguero-Valverde, 2013).

Most studies which have investigated the safety factors affecting crash occurrences focused on the effect of roadway geometric characteristics. Haynes et al. (2007) studied how road curvature affects the crash frequency and found that the cumulative angle was the most strongly related measure to fatal crashes. Noland and Oh (2004) indicated that relationships between crash occurrences and the number of lanes, the lane width and the shoulder width were significant. Furthermore, a series of studies investigated various vertical and horizontal alignment factors and tried to find the relationships between different characteristics and crashes (Shankar et al., 1995; Garber and Wu, 2001; Ma et al., 2008).

The traffic factors are also found to be closely related to the crash occurrence. The annual average daily traffic (AADT) was used in many studies and a significant direct relationship with the crash occurrence was found (Milton and Mannering, 1998; Abdel-Aty and Radwan, 2000; Zhang et al., 2012). Yu et al. (2013) investigated the real-time traffic data, incorporated with weather data, and the crash frequency. The study showed that the average speed was significantly related to crashes. Kononov et al. (2012) applied an empirical examination of the relationship of volume, density, and speed with the crash occurrences and suggested a combined threshold of speed and density for the increase of the crash rate.

No consistent conclusion has been got about the relationship between congestion and crash occurrences in the existing studies. Noland and Quddus (2005) investigated the differences of safety factors during fixed congested and uncongested periods. Quddus et al. (2009) focused on how traffic congestion influences crash severity and found that more severe congestion may result in less severe crashes. Wang et al. (2013) found an inverse result and indicated that traffic congestion has little impact on slight injury crashes. A recent study by Harwood et al. (2013) found a U-shaped relationship between crash rates and congestion. These studies confirmed that the crash mechanisms are varied in different traffic situations. However, no studies have investigated the differences and similarities of safety factors in non-congested and congested flow based on the real-time traffic flow condition. Thus, the corresponding countermeasures can be taken, especially for dynamic traffic management requirements.

3. Study area and data preparation

3.1. Study area

The Shanghai urban expressway system, including North-South Elevated road, Yan-an Elevated road, Inner Ring and Middle Ring Elevated road, was selected as the study area (cf. Fig. 1). The traffic composition among the whole urban expressway system is similar: 98% passenger cars and 2% coach. The speed limit is 80 km/h. The entire expressway system was divided into 172 segments by two successive ramps. Five segments were excluded because of missing traffic flow data. Finally, a total of 167 expressway segments were included in this analysis.

3.2. Crash data

Because the problem of missing crash records are far from rare in the China Public Security Bureau, to ensure the data quality and accuracy, crash frequency data were extracted from the video records of SEES directly and manually. From October 2010 to September 2013, a total of 48,325 crashes were collected in the three-year period. Each crash datum includes the crash event type, crash date, beginning and ending time point, crash location, weather information, traffic condition, etc. The non-congested-flow crashes (NCFC) and congested-flow crashes (CFC) can be distinguished by real time traffic data. Due to the method of crash collections, the severity of the crash (e.g., fatal, injury or property damage only crash) was not available in this study.

3.3. Traffic flow data

The traffic flow data were collected by dual loop detectors installed on the expressways. The vehicle volume, average speed, and average time occupancy can be acquired in 20-s intervals from the detector. The average daily traffic (ADT) is calculated according to the dual loop detector data. Because crashes under different traffic flow conditions were studied separately, the average daily non-congested traffic (ADNCT) and the average daily congested traffic (ADCT) were both calculated to reflect the different traffic volumes. According to the traffic management standard of Shanghai, the speed threshold for congestion and non-congestion was set as 40 km/h for urban expressways in Shanghai. When the average speed is higher than 40 km/h, the traffic is regarded as non-congested flow; otherwise, the traffic is regarded as congested flow. The equations for ADT, ADCT and ADNCT are:

$$ADCT = \frac{c_1 + \cdots + c_i + \cdots + c_n}{n} \quad (1)$$