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Analyzing crash frequency in freeway tunnels: A correlated random parameters approach

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ABSTRACT

The majority of past road safety studies focused on open road segments while only a few focused on tunnels. Moreover, the past tunnel studies produced some inconsistent results about the safety effects of the traffic patterns, the tunnel design, and the pavement conditions. The effects of these conditions therefore remain unknown, especially for freeway tunnels in China. The study presented in this paper investigated the safety effects of these various factors utilizing a four-year period (2009–2012) of data as well as three models: 1) a random effects negative binomial model (RENB), 2) an uncorrelated random parameters negative binomial model (URPNB), and 3) a correlated random parameters negative binomial model (CRPNB). Of these three, the results showed that the CRPNB model provided better goodness-of-fit and offered more insights into the factors that contribute to tunnel safety. The CRPNB was not only able to allocate the part of the otherwise unobserved heterogeneity to the individual model parameters but also was able to estimate the cross-correlations between these parameters. Furthermore, the study results showed that traffic volume, tunnel length, proportion of heavy trucks, curvature, and pavement rutting were associated with higher frequencies of traffic crashes, while the distance to the tunnel wall, distance to the adjacent tunnel, distress ratio, International Roughness Index (IRI), and friction coefficient were associated with lower crash frequencies. In addition, the effects of the heterogeneity of the proportion of heavy trucks, the curvature, the rutting depth, and the friction coefficient were identified and their inter-correlations were analyzed.

1. Introduction

While a large number of studies have been conducted to investigate the safety effects of traffic flow, geometric design, and environmental characteristics or weather conditions on open roads, the contributing factors to traffic safety in tunnels have rarely been studied and compared to the safety factors on open roads. As tunnels are usually less illuminated and have cross-sections that are more constrained than open roads, they may increase the anxiety among drivers and alter their behavior. In addition, the rapid change in the illumination in the tunnel entrance and exit zones that requires drivers to visually adjust quickly may temporally lessen driver performance (PIAR, 2008). Thus, driving in a tunnel requires more alertness and additional mental work, which in turn results in more challenging safety conditions and may contribute to safety reduction compared to open roads.

The previous studies pertaining to traffic safety factors in tunnels are few in number and simply utilized the crash rate (number of crashes per million vehicle-kilometers) to evaluate the safety conditions. Lemke (2000) found that the crash rate was higher in long tunnels than in short ones; but the reverse result was obtained by Amundsen and Ranes (2000), who also found that the crash rate was low for tunnels with high traffic volumes. However, advancements in the methodologies used for data collection and analysis have produced new techniques to analyze the crash characteristics in tunnels. For example, a negative binomial model was recently used to identify the factors affecting crash frequency in road tunnels (Caliendo et al., 2013). The results showed that number of crashes in tunnels was positively related to the annual average daily traffic (AADT) and percentage of trucks. The car following behavior affecting tunnel safety also was explored using traffic conflict techniques (Yeung and Wong, 2014). In addition, data collected from a driving simulator was used to evaluate the safety effects of tunnel design and lighting, and that study's results concluded that light-colored tunnel walls can be safety beneficial (Kircher and Ahlstrom, 2012).

The small number of studies on the factors of traffic safety in tunnels indicates a gap in the knowledge of this subject and more effort is needed to better understand and improve the design of tunnels and management of them. Most of the previous studies focused on tunnels

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where traffic and driving behavior, as well as tunnel design, were considerably different from those in China. The three studies addressing Chinese tunnels (freeway and urban) focused on either the spatial distribution of tunnel crashes (Ma et al., 2009; Ma et al., 2016) or traffic behaviors (Jiang et al., 2016). Although useful and revealing, these studies were not able to provide much guidance on tunnel design and management in China.

Negative binominal (NB) models are widely used for analyzing crash frequency. They properly represent crash counts as non-negative, integer, and often over-dispersed (Miaou and Lum, 1993; Shankar et al., 1998; Donnell and Mason, 2006). However, the conventional version of this model (fixed parameters negative binomial (FPNB)) assumes that the parameters are single-valued and consequently fails to capture the heterogeneity attributed to these effects and manifested by the variability of the parameters across the observations. This omission can lead to biased parameter estimation and incorrect inferences (Washington et al., 2010). To fill this methodological weakness, an alternative NB model (random parameters negative binomial (RPNB)) was advocated by a number of researchers in recent years to account for the unobserved heterogeneous effects of various factors (Chen and Tarko, 2014; Xu and Huang, 2015; Truong et al., 2016; Xu et al., 2017; Rusli et al., 2017). They provided examples that confirmed the new RPNB model was superior to the conventional NB model. Note that the RPNB model reduces to a random effects negative binomial (RENB) model if only the constant term of the model is a random parameter (Washington et al., 2010; Chen and Tarko, 2014).

Almost all the existing studies assumed that the heterogeneous effects are independent one from another and, consequently, there is no correlation among these parameters. However, this is not always true, and ignoring the interactive effects may result in biased estimations and restrictive inferences (Conway and Kniesner, 1991). In the study presented in this paper, a correlated random parameters negative binomial (CRPNB) model was designed that could account for the heterogeneous effects of the contributing factors together with their interactive component.

This study contributes to the knowledge base in the following three ways. First, rarely-studied factors of tunnel traffic safety, such as tunnel pavement conditions, were investigated. Second, the results from this study provide additional understanding of the safety effects that are believed to be beneficial for the traffic control, geometric design, and maintenance of freeway tunnels in China. Third, the presented study confirms the advantages of the CRPNB model, which accounts for the heterogeneous effects and their interaction component manifested through the correlation between the parameters.

2. Data description

The data for this study were collected from 24 tunnels totalling 28.5 km in length located on three Chinese freeways: Jingzhu Freeway (G4), Yuegan Freeway (G35), and Shendan Freeway (G1113). The crash data included 323 crashes that occurred in these tunnels during the four-year period 2009 through 2012. The former two freeways are managed by Guangdong Province, and the third freeway is managed by Liaoning Province. All the tunnels are four-lane twin-bore tunnels with two lanes in each direction. The data included crashes, traffic volumes, geometric design characteristics, and pavement conditions.

The crash data were obtained from the Guangdong Provincial Freeway Administration (GDFA) and the Liaoning Provincial Freeway Administration (LNFA). The AADT for nine types of vehicles (four types of cars classified by the number of seats and five types of trucks classified by load capacity) were estimated based on the Volume Observation Station counts on the studied freeways and provided by GDFA and LNFA for each studied year. Freeway geometric design data containing detailed tunnel design elements were obtained from the Guangdong Provincial Communications Survey and Design Institute and the Liaoning Provincial Communications Survey and Design Institute. Pavement condition measurements at the frequency of 10 or 20 m for each studied year were obtained from Highway Test and Maintenance Center of GDFA and LNFA. The three freeways were divided into homogeneous segments in respect to their design and traffic. Then, the annual data, including the number of crashes in each of four years (2009–2012), were linked to the corresponding freeway segments with the help of kilometer markers, and the average pavement condition was calculated for each segment. Finally, the data for the tunnels for this study were extracted.

The longitudinal grades in freeway tunnels are much smaller than elsewhere as are the differences between homogeneous segments. This design allowed merging the original homogeneous segments to avoid segments that were too short. Thus, the final tunnel segmentation was based on the homogeneity of the geometric design characteristics excluding vertical alignment. Yet, the difference between the longitudinal grades within the merged segments never exceeded 2%. The steepest longitudinal grade in each segment represented the vertical alignment of a segment for the purpose of safety analysis. The responsible freeway authority confirmed that none of the studied segments had undergone any alteration or experienced long closures during the analysis period. Furthermore, the studied tunnels were videotaped in each direction with a high-definition camera to check the consistency of the existing tunnel with the tunnel design documentation. The kilometer and hectometer markers were clearly seen on the video and were used to link the video-based observations with the data. The described and executed procedure yielded a sample of 312 observations (39 homogeneous segments × 2 directions × 4 years) with 323 crashes that were assembled and analyzed.

The descriptive statistics of crashes, traffic characteristics, tunnel designs, and pavement conditions are presented in Table 1.

The pavement condition variable – *distress ratio*, also called damage ratio – represents the extent of surface distress such as cracking, ravelling, and sinking. *International Roughness Index* (IRI) is the index

Table 1
Descriptive statistics of variables.

Variables	Mean	Std Dev.	Minimum	Maximum
Dependent variable				
Number of crashes	1.049	1.776	0	12
Traffic characteristics				
AADT (veh/day)	4740	1739	1468	10677
Proportion of heavy trucks	0.255	0.157	0.073	0.545
Tunnel design				
Length of segment (km)	0.732	0.291	0.293	1.613
Length of tunnel (1 if tunnel is longer than 500 m, 0 otherwise)	0.412	0.493	0	1
Distance from edge of outside lane to tunnel wall (1 if 1.75 m, 0 if 1.5 m)	0.266	0.443	0	1
Distance between two tunnels (km)	8.959	8.257	0.040	20
Tunnel entrance indicator (1 if including tunnel entrance, 0 otherwise)	0.861	0.367	0	1
Tunnel exit indicator (1 if including tunnel exit,0 otherwise)	0.861	0.367	0	1
Curvature (1/km)	0.417	0.453	0	1.667
Length of tangent in tunnel (km)	0.910	0.942	0	2.110
Steep downgrade indicator (1 if largest grade is less than −2%, 0 otherwise)	0.201	0.402	0	1
Steep upgrade indicator (1 if largest grade is greater than 2%, 0 otherwise)	0.250	0.434	0	1
Pavement condition				
Distress ratio (%)	0.088	0.160	0	1.901
Rutting depth (mm)	6.018	1.885	1.522	22.850
International roughness index (m/km)	2.787	1.526	0.194	5.408
Friction coefficient	44.099	16.525	12.520	71.524
Structure strength indicator	3.338	1.917	0.649	7.568