Accident Analysis and Prevention 111 (2018) 56–62

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Interactive risk analysis on crash injury severity at a mountainous freeway with tunnel groups in China

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ARTICLE INFO

Keywords:
Mountainous freeway
Tunnel group
Interactive effect
Injury severity
Hazardous driving event

ABSTRACT

Traffic safety of freeways has attracted major concerns, especially for a mountainous freeway affected by adverse terrain conditions, constrained roadway geometry and complicated driving environments. On the basis of a comprehensive dataset collected from a mountainous freeway with a length of 61 km but gathering 12 tunnels, this study seeks to examining the interactive effect of mountainous freeway alignment, driving behaviors, vehicle characteristics and environmental factors on crash severity. A classification and regression tree (CART) model is employed as it can deal with high-order interactions between explanatory variables.

Results show that the driving behavior is the most important determinant for injury severity of mountainous freeway crashes, followed by the crash time, grade, curve radius and vehicle type. These variables, interacted with the factors of season and crash location, may largely account for the likelihood of high risk events which may result in severe crashes. Events associated with a notably higher probability of severe crashes include coach drivers involved in improper lane changing and other improper actions, drivers involved in speeding during afternoon or evening, drivers involved in speeding along large curve and straight segment during morning, noon or night, and drivers involved in fatigue while passing along the downgrade. Safety interventions to prevent severe crashes at the mountainous freeway include hierarchical supervision in terms of hazardous driving events, enhanced enforcement for speeding and fatigue driving, deployment of advanced driving assistance systems for fatigue driving warning, and cumulative driving time monitoring for long-distance-travel freight vehicles.

1. Introduction

The past decade has witnessed a rapid increase in length of mountainous freeways in the middle and western regions of China under the national freeway network improvement strategy. Recently, traffic safety of mountainous freeways has attracted major concerns, especially when it interacts with frequently-occurred extreme weather and insufficient subsidiary facilities in those mountainous areas. For instance, in Hunan Province, the total length of operating freeways reaches 6000 km, of which more than half of the segments transverse mountainous areas with a large number of tunnels. By the crash report in 2013 (National Bureau of Statistics of China, 2014), while the freeway accounts for merely 2.2% of the highway mileage, freeway road users represent more than 22% of total traffic fatalities. Affected by the adverse terrain, the mountainous freeway has unique features such as constrained roadway geometry and complicated driving environments. High slope, long downhill, viaduct, tunnel and tunnel groups explicitly differentiate mountainous freeways from those in flat areas. As a cost-effective engineering means of traversing mountainous regions, tunnels play an important part and have become gradually extensive in mountainous freeway systems. If a crash occurs in tunnel, the influence is generally stronger than on open stretches of road (Amundsen and Ranes, 2000; Ma et al., 2009; Jian and Wong, 2013), the outcome can be extremely destructive and catastrophic. A comprehensive investigation of risk factors influencing crash injury severity at a mountainous freeway with tunnel groups is vital since professionals in roadway design, freeway management, enforcement, and education and awareness could benefit from this information to decrease severe traffic crashes.

Considerable studies have investigated the extensive array of factors that contribute to freeway injury severity for interstate freeway (Xu et al., 2013; Yu and Abdel-Aty, 2014a,b), freeway tunnels (Ma et al., 2016), freeway merge and diverge areas (Wang et al., 2009; Zhang et al., 2011; Mergia et al., 2013), urban freeway (Haleem and Gan, 2013), and mountainous freeway (Yu and Abdel-Aty 2014a,b). These significant factors include grade (Yu and Abdel-Aty, 2014a,b), curve (Wang et al., 2009), location (Haleem and Gan, 2013; Chu, 2013; Ma et al., 2016), number of lanes (Wang et al., 2009; Zhang et al., 2011;

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https://doi.org/10.1016/j.aap.2017.11.024
Received 29 July 2017; Received in revised form 1 November 2017; Accepted 17 November 2017
0001-4575/

Mergia et al., 2013), alcohol involvement (Zhang et al., 2011; Chu, 2013; Mergia et al., 2013), speeding (Mergia et al., 2013), fatigue driving (Chu, 2013), vehicle type (Haleem and Gan, 2013; Mergia et al., 2013; Yu and Abdel-Aty, 2014b), impact point (Haleem and Gan, 2013; Yu and Abdel-Aty, 2014b), crash types (Wang et al., 2009; Zhang et al., 2011; Mergia et al., 2013), surface conditions (Wang et al., 2009; Zhang et al., 2011), time of day (Chu, 2013; Yu and Abdel-Aty, 2014b; Ma et al., 2016), weather (Wang et al., 2009; Zhang et al., 2011; Mergia et al., 2013; Yu and Abdel-Aty, 2014a; Ma et al., 2016), season (Yu and Abdel-Aty, 2014a,b; Ma et al., 2016), and light condition (Wang et al., 2009; Zhang et al., 2011; Mergia et al., 2013).

In view of the fact that injury severity of freeway crashes is the result of combination of multiple factors, it is likely that no single factor can be identified to provide a complete explanation for the high risk of severe crashes in freeways. At mountainous freeways with tunnel groups, the sophisticated interaction of the adverse terrain, road facilities, environmental factors and driving behaviors, may greatly elevate the likelihood of crash occurrence and injury severity. To take an example for driving through a tunnel, before entering the tunnel, the reflection of sun light from the tunnel portal might cause temporary ocular blindness. After entering the tunnel, drivers need to adapt to abruptly change in light condition, resulting in poor sight condition. After exiting the tunnel, different light conditions and/or unexpected weather conditions will dangerously distract drivers' attention and challenge drivers' responses in a short time (Ma et al., 2016). Furthermore, complex road geometry and environment conditions as well as different speed limits between in tunnels and on open sections shall also increase the risk of injury and fatal crashes (Bassan, 2015).

From a methodological standpoint, statistical regression analysis, such as binary logit/probit model (Yu and Abdel-Aty, 2014b), ordered logit/probit model (Zhang et al., 2011; Abegaz et al., 2014; Ma et al., 2016), partial proportional odds model (Wang et al., 2009), multinomial logit model (Çelik and Oktay, 2014), and mixed logit model (Chen and Chen, 2013; Haleem and Gan, 2013) have been widely employed to analyze the injury severity. However, because of the mass of complicated data on freeway crashes, traditional regression models may not be the best choice for investigating the predictors and their interaction effects on injury severity of freeway crashes. Firstly, regression models generally have their own model assumptions and predefined underlying relationships between the target variable and predictors. The violation of model assumption could result in erroneous estimations of injury likelihood (Chang and Chien, 2013; Chang and Wang, 2006). Secondly, although some regression models could account for intricate interactions associating with variable interaction terms, there are still limitations in analysis of high-order interactions between explanatory variables and the rank of variable importance (Haleem and Gan, 2013; Jung et al., 2016). Furthermore, for situations where there are many possible explanatory variables including all possible interactions, variable selection for the regression models would be an issue.

Classification and Regression Trees (CART) method, as a commonly used data mining technique, can capture non-additive behaviors, which provides the ability to highlight sophisticated relationships that are difficult to discover. When CART analysis is applied, variable correlation problems are not problematic (Breiman et al., 1984). In addition, CART model can boost the efficiency when it deals with large-scale data containing a large number of explanatory variables and produce useful results using only a few essential variables with a brief graphic display (Chang and Wang, 2006; Chang and Chien, 2013; Jung et al., 2016). Recently, researchers have attempted to employ CART model to explore the determinants of injuries for such as motorcycle pillion passengers (Tavakoli et al., 2014), pedestrians (Jung et al., 2016), bicyclists (Prati et al., 2017), rural road users (Kashani and Mohaymany, 2014) and truck-involved crash casualties (Chang and Chien, 2013). Nonetheless, to the best of our knowledge, no study has used CART model to investigate the interactive effects between multiple factors on injury severity of freeway crashes.

The present study intends to narrow such an existing gap by looking into injury severity in crashes occurring at mountainous freeway with tunnel groups. The CART model is employed to model injury severity based on a comprehensive dataset collected from a mountainous freeway in Hunan province of China, with the length of 61 kilometers but gathering 12 tunnels. We aim at (1) examining the interactive impact of mountainous freeway alignment, driving behavior, vehicle characteristics and environmental factors on crash severity, (2) identifying pre-crash hazardous driving events associated with high likelihoods of severe crashes, (3) providing evidence-based safety interventions in enhancing the mountainous freeway safety.

2. Data

The freeway section under consideration is a four-lane freeway with a length of 61 kilometers (starting at Kilometer Marker 1341.000 in Dongkou and ending at Kilometer Marker 1402.000 in Anjiang), which is a part of the freeway connecting the cities of Shanghai and Kunming, located in the west of Hunan Province. The selected section gathers twelve tunnels with one-way traffic in two tubes, passing through the extreme mountainous area. The lengths of these tunnels range from 155 m to 6956 m with an average of 1122 m, as shown in Fig. 1. Most of spacing distances between adjacent tunnels are less than 1000 m, and the shortest spacing distance is only 72 m. This selected section is a typical mountainous freeway with tunnel groups

Crash data obtained from Hunan Provincial Public Security Ministry were extracted from the Traffic Management Sector-Specific Incident Case Data Report, which is only officially available, most detailed and reliable source of traffic crash data in China. Data are recorded and reported by the traffic polices who conduct on-scene assessments and provide feedback within 24 h to the headquarters of the Traffic Management Department. This data report covers different aspects of a traffic crash, including demographic characteristics of the casualties, degree of casualties, collision types, liability types, pre-crash driving behaviors, road types, vehicle types, and environment factors such as weather conditions, the precise crash time and location of the crash. A total of 1537 crashes were reported in the selected freeway section from October 2011 to September 2016. The injury severities recorded by traffic police are categorized as property damage only, injury (i.e., non-disability injury, disability injury) and fatality (i.e., immediate or subsequent death from injuries within 7 days after a crash). There were 1442 PDO crashes, 71 injury crashes and 24 fatal crashes, respectively. In this study, crashes were classified as non-severe crashes (PDO crashes only) and severe crashes (injury and fatal crashes).

Previous researches suggested that the roadway geometry such as grade and curve were important factors influencing injury severity of freeway crashes (Wang et al., 2009; Yu and Abdel-Aty, 2014a,b). In this study, we also obtained detailed roadway geometry data for the selected freeway from Expressway Management Bureau of Hunan Province. The uphill section has longitudinal grades up to about 4% while downhill section has grades that vary from 0.3% to 4.85%. The horizontal curve radius ranges from 640 m to 10,000 m. For each specific crash, the corresponding roadway geometry (grade and curve radius) features were identified and matched. To facilitate the analysis and enhance the statistical validity, the grade was transformed to categorical variable. The grades within 2% were categorized, resulting in 4 categories including 2 categories for downgrade (being negative) and 2 types for upgrade (being positive). Curve radius was treated as a numerical variable by retaining its original format.

Because there are differences in lighting conditions between outside tunnels and inside tunnels, and variations in perceptions and attitudes of drivers when they approach and drive away from the tunnel, it is reasonable to extend the zone in front of the tunnel openings as a tunnel affected area. The design speeds of inside tunnel section and outside tunnel section are 80 km/h and 100 km/h, respectively. The response