Tunnelling and Underground Space Technology 82 (2018) 358–365

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Crash analysis of Chinese freeway tunnel groups using a five-zone analytic approach

Jie Wang[a], Amjad Pervez[a], Zhengwu Wang[b], Chunyang Han[a], Lanye Hu[a], Helai Huang[a,*]

[a] School of Traffic and Transportation Engineering, Central South University, Changsha 410075, China
[b] School of Traffic and Transportation Engineering, Changsha University of Science & Technology, Changsha 410004, China

ARTICLE INFO

Keywords:
Crash
Tunnel group
Connection zone
Light

ABSTRACT

For mountainous freeways, some tunnels are situated adjacent to each other resulting in the tunnel group. This study aims to investigate the characteristics of traffic crashes in freeway tunnel groups. A typical mountainous freeway with tunnel groups in China is studied using police-reported crash data. A five-zone approach is proposed for safety analysis of tunnel groups. The result shows that the connection zone has the highest crash rate. Interior entrance zone has a significantly higher proportion of crashes during the daytime compared with other four zones, while the exit impact zone is associated with a higher proportion of crashes during the nighttime. This indicates that crashes are more likely to occur when a vehicle moves from bright to dark environments. Findings in this study shed some light on the engineering and policy implications for raising traffic safety of freeway tunnel groups.

1. Introduction

Highway tunnels can improve road alignments, reduce the destruction of vegetation, and protect the ecological environment. But due to its semi-enclosed space structure, the driving environment in the tunnels is different from that of the open road sections. The relatively dark, narrow, and noisy environment would bring anxiety and panic to the drivers (PIARC, 2008). Another effect is the drastic changes in the visual environment at the tunnel entrance and exit that might induce temporary ocular blindness. In addition, due to limited inner space, collisions in the tunnel are often more difficult to rescue, resulting in crashes with wide impacts, and with a high probability of secondary crashes (Amundsen and Ranes, 2000).

The length of mountainous freeways is increasing in the middle and western regions of China under the national freeway network improvement strategy (Huang et al., 2018). For these mountainous freeways, tunnels account for a substantial proportion. Some of these tunnels are situated adjacent to each other resulting in the tunnel group section. When driving through the tunnel group, the extremely frequent change in the visual environment that requires drivers to visually adjust quickly, which in turn results in more challenging safety conditions and may contribute to safety reduction (Zhao et al., 2011). Recently a traffic crash occurred at the Shanxi Qinling Tunnel Group on August 10, 2017, in which a coach collided with the tunnel portal, causing the death of 36 people and injuring 13 people. In the past five years, the number of traffic crashes (injury and death crashes) in freeway tunnels in China increased by 25%, from 244 in 2012 to 305 in 2016. Correspondingly, the number of deaths caused by freeway tunnel crashes increased by 76%, from 106 deaths in 2012 to 187 deaths in 2016 (Traffic Administration Bureau of the Ministry of Public Security, 2017). It is essential to investigate the characteristics of tunnel traffic crashes in order to reveal the mechanism of crash initiation and to seek for the effective measures to prevent tunnel crashes.

Driving experiment studies have been widely adopted to examine the driver's visual adaptation and driving speed variations when entering and exiting the tunnel. Zhao et al. (2011) examined visual parameters (fixation duration, saccade amplitude and number of fixations) when driving through a tunnel group section, and found that the visual parameters of drivers at the entrance and exit of the tunnel group are significantly different from those of a single tunnel. Du et al. (2007) established a driving safety evaluation index based on the driver's pupil movement to evaluate the visual comfort degree and driving safety of tunnel entrance and exit. Hu et al. (2014) developed a logistics regression model for the rate of change of driver's pupil movement, luminance reduction coefficient and vehicle operating speed at the tunnel entrance section, and used the model to determine the comfort luminance reduction coefficient of tunnel entrance section at a speed of 60 km/h.

---

[*] Corresponding author.
E-mail address: huanghelai@csu.edu.cn (H. Huang).

https://doi.org/10.1016/j.tust.2018.08.037
Received 12 January 2018; Received in revised form 10 June 2018; Accepted 17 August 2018

Table 1
Crash rates (crashes per million vehicle·km) for tunnel zones in previous studies (Bassan, 2016).

Study	Tunnel type (Country)	Zone 1	Zone 2	Zone 3	Zone 4	Inside tunnel (zones 2–4)
Amundsen and Ranes (2000)	All tunnels (Norway)	0.30	0.23	0.16	0.10	0.13
Ma et al. (2009)	Freeway tunnel (China)	0.56	0.53	0.58	0.45	0.50
Yeung and Wong (2013) (Crashes/km/year)[a]	Expressway tunnels (Singapore)	52	35[b]	5	NA	

[a] Different measurement units of crash rate in the study of Yeung and Wong (2013).

[b] The value of crash rate is for entry transition zone that combines Zone 1 and Zone 2.

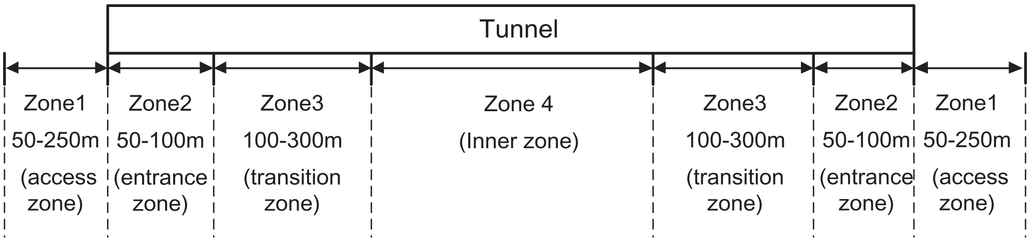

Fig. 1. Typical tunnel zones for crash analysis in previous studies (Bassan, 2016).

Table 2
A summary of main findings in previous studies.

Study	Main findings
Amundsen and Ranes (2000)	(1) Crash severity was somewhat higher in tunnels than on national road network in general. (2) Crash rate in the access zone was the highest (zone1), followed by the entrance zone (zone2). (3) Crash rate declined noticeably with increasing tunnel lengths. (4) Significant differences in crash rates existed between single-tube two-way tunnels and double-tube one-way tunnels.
Ma et al. (2009)	(1) Crash severity was somewhat higher in freeway tunnels than on the open road. (2) Crash rate was the highest in the transition zone (zone3). (3) Most of the tunnel traffic crashes occurred in January. (4) Tunnel traffic crashes taken place in three peak periods, namely 5:00–7:00, 9:00–10:00 and 15:00–17:00.
Yeung and Wong (2013)	(1) Crashes in the interior zone were more serious than that in the transition zone. (2) Crash rate was higher in the transition zone (zone2) compared to the interior zone (zone3), being mostly attributed to multivehicle crashes. (3) Crash rate of tunnel entrance was higher than that of tunnel exit.

Researchers have also attempted to study tunnel crash characteristics and factors affecting crash occurrence or severity based on historical police-recorded crash data. Ma et al. (2015) applied logit regression method to establish injury severity model of crashes in freeway tunnels, and found that season, time of day, location of crash, tunnel length, and adverse weather are significant factors. Caliendo et al. (2013) employed a bivariate negative binomial regression model to analyze the influence of tunnel length, traffic volume, truck ratio, and lane number on the crash counts by injury severity in road tunnels. Meng and Qu (2012) developed a rear-end crash frequency estimation model to reflect the relationship between time to collision (TTC) distributions and the rear-end crash frequencies. Several studies (Amundsen and Ranes, 2000, Ma et al., 2009, Yeung and Wong, 2013) investigated the tunnel crashes by dividing the tunnels into different zones based on the discrepancy of the driving environment, then analyzed and compared the crash rate, crash severity, collision type for each zone. Table 1 depicts a comparison of crash rate for tunnel zones according to three previous studies. A typical sketch of the tunnel zones is presented in Fig. 1, and the main findings are summarized in Table2. These previous studies are focused on single tunnels rather than tunnel groups. When driving through the tunnel group, the driver would experience a frequent change in driving environment temporarily, and the zone division and crash characteristics of tunnel group may differ from the single tunnel.

Although driving behaviors and traffic safety in the single tunnels have been widely studied, empirical evidence for crash characteristics of tunnel group is still scarce. This study intended to (1) propose a five-zone analytic approach for the safety of freeway tunnel group, (2) examine crash rates of each zone of the tunnel group based on the historical crash data, and (3) explore the effect of light conditions (night and daylight) on the crash occurrence of each zone.

2. Method

2.1. Zone definition

According to tunnel design specifications (JTG/T D70/2-2014) (Ministry of Transport of the People's Republic of China, 2014a), road tunnels can be divided into four categories: short tunnels ($L < 500$ m), medium tunnels ($500\text{ m} \le L < 1000$ m), long tunnels ($1000\text{ m} \le L < 3000$ m), and extra-long tunnels ($L > 3000$ m). However, the tunnel group has not been specifically defined in this specification. Several studies (Yu et al., 2012; Zhu and Pan, 2014) suggested that adjacent tunnels can be identified as a tunnel group if the driver is affected by the subsequent tunnel during the light adaptation process as the driver goes out of the former tunnel. As shown in Fig. 2, T1 and T2 are two adjacent tunnels and L is the distance between them. D_1 is defined as the light adaptation distance, covering a distance over which required for the drivers to adapt to the natural light during the day-time after exiting the T1. D_2 is defined as the fixation point distance, covering a distance over which an approaching driver can see the portal of T2. If the distance between two adjacent tunnels (L) is less than the sum of D_1 and D_2, the light adaptation will affect the driving process of approaching the T_2. In that case, such adjacent tunnels cannot be treated as single tunnels but should be considered as a tunnel group.

The light adaptation time is regarded as 15 s in this study, based on