Research Article
Statistical Analysis of Traffic Accidents in Shanghai River Crossing Tunnels and Safety Countermeasures

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A large number of traffic tunnel accidents have been reported in China since the 21st century. However, few studies have been reported to analyze traffic accidents that have occurred in urban road tunnels. This study aims to examine the characteristics of the temporal, spatial, and modality distribution of traffic in Shanghai river crossing tunnels using statistical analysis and comparative analysis. Employing these techniques tunnel accident data obtained from Shanghai center 110 was analyzed to determine temporal and spatial distribution characteristics of traffic accidents in river crossing tunnels in Shanghai. The results of this analysis are discussed and summarized in this paper. Identification of the characteristics of tunnel traffic accidents can provide valuable information for development of effective countermeasures to improve tunnel safety in China.

1. Introduction

Tunnels play an important role in urban transportation networks in large cities in China. As shown in Figure 1 [1], the introduction of new of road tunnels in China has rapidly increased since the beginning of the 21st century. According to a 2012 Chinese government bulletin, by end of 2011 there were 8522 road tunnels in China with total length of about 6.2534 million meters. In 2011, 1138 road tunnels with total length of 1.1309 million meters were constructed. As the number of tunnels has increased, so has the number of traffic accidents in these tunnels. In comparison to open roadways, traffic accidents in long tunnels are relatively rare, but the complex problems of a tunnel accident result in casualties, property damage, and greater social impact [2–5].

In comparison to open roadways, tunnels have some unique characteristics due to their confined nature. Consequently, when a traffic accident occurs, a tunnel can quickly become a fatal trap for motorists due to poisonous smoke inhalation and high temperatures if the accident results in a fire [6, 7].

A number of research studies have been conducted to study traffic tunnel safety. One such study, conducted by Amundsen and Ranes in 2000 [8] considered traffic accidents in 900 road tunnels on national and county roads. These author’s results showed that tunnels had similar safety performance when compared with high standard modern roads. However, at tunnel the entrance zone accident rates were higher and more severe when compared to surface roads. Similarly, the average frequency of fires in tunnels was found to be higher than on open roads. In addition, in some tunnels the frequency of fires involving heavy commercial vehicles was much higher than that of passenger cars according to the research in 1998 by PIARC [9]. Although accident rates appeared to be slightly lower in tunnels than on open roads, accidents that occur in tunnels could have greater peripheral impact [10]. In contrast to the prevailing opinion, a recent study concluded that accident rates were lower in tunnels than on open roads and accidents with severe injuries and property damages in tunnels were less frequent than those on open roads [11]. Haack [12] agreed with these conclusions claiming that current safety issues in tunnels can lead to improved vehicle control states resulting in safety improvements on tunnel roads.
In China, with the rapid development of tunnel construction and subsequent high rate of tunnel accidents, tunnel traffic safety has acquired greater attention from traffic safety engineers. In 2006, traffic accidents in the Shaoguan tunnel in Jingzhu were examined and safety countermeasures were proposed by Zhang et al. [13]. In 2008, based on a statistical analysis of traffic accidents in four tunnels in Beijing-Zhuhai freeway, temporal, spatial, and modality distribution and accident type distribution were discussed by Ma et al. [14]. In 2009, Lin et al. [15] used tunnel traffic detector data to examine the spatial and temporal variations of capacity, free-flow speed, passenger car equivalent of buses, and speed-flow relationships. In 2009, Zhang et al. [16] discussed the relationships between traffic accidents, fire accidents, rear-end accidents, wall colliding accidents, and vehicle roll-over accidents with traffic volumes and some countermeasures were suggested to decrease traffic accidents in expressway tunnels. In 2010, Ma et al. [17] conducted logistic model research to determine the factors which affect accident severity in highway tunnels. It was found that the time of the accident, the collision type, the weather conditions, and the ratio of daily PCU to AADT are the most significant factors in the severity of a vehicular accident.

However, despite of these research findings, few studies have been reported to focus on traffic accidents in urban river crossing tunnels. Therefore, using the Shanghai river crossing tunnels as the subject we employed statistical and contrastive analyses to define the temporal distribution, spatial distribution and accident type distribution analyzes of accident severity and the relationship between road classifications in Shanghai river-crossing tunnels.

2. Data Basis

This study was based on data collected by Shanghai Center 110, which provided details on traffic accidents in traffic tunnels in Shanghai. Each accident record includes detailed information including time, geographic coordinates, location, case category, and a detailed case description. Accidents in thirteen river crossing tunnels were selected for this study. The supporting data on river crossing tunnels such as tunnel length, lanes, design speed, and road classification were collected from Shanghai Tunnel Engineering & Rail Transit Design and Research Institute.

Using the methods of Amundsen and Ranes, data on accidents and locations were retrieved from the Shanghai Center 110 and were grouped into the following four categories as shown in Figure 2 [8].

Zone 1: the first 50 m in front of the tunnel openings.
Zone 2: the first 50 m inside the tunnel.
Zone 3: the next 100 m inside the tunnel.
Zone 4: the mid-zone, that is, the remainder of the tunnel.

Tunnels shorter than 100 m only have zones 1 and 2; tunnels shorter than 300 m do not have a mid-zone (i.e., zone 4). In this paper, all tunnels are no less than 1000 m and, therefore, have four zones.

3. Temporal Distribution of Traffic Accidents

Temporal characteristics of accidents refer to the characteristics of accidents that vary over time. Analyzing the temporal distribution can reveal the trend of accidents but can also give the basis for further research on the causation of those accidents [18]. In addition to annual surveys, temporal characteristics of accidents can also be studied by analyzing the monthly and hourly distribution of traffic accidents. Consequently, this paper will make a detailed study of the temporal characteristics of traffic accidents by analyzing the weekly and hourly distributions of these incidents.

3.1. Weekly Distribution of Traffic Accidents

Patterns of city life and daily commuting impact the weekly distribution of tunnel accidents. As is shown in Figure 3, accidents occur more frequently on Monday and Friday while the occurrence of accidents on weekends was lower than on weekdays. This could be attributed to the pattern of city life and daily commuting in Shanghai. Similar results were also found by researchers in Victoria, Australia, [19] where accidents were more likely to occur on weekdays than weekends.

3.2. Hourly Distribution of Traffic Accidents

The hourly profiles of vehicle trips in Shanghai are shown in Figure 4. As can be seen in Figure 4 [20], trip time is concentrated on two peak periods, 7:00–9:00 and 16:00–18:00. The hourly distribution of traffic accidents in Shanghai river tunnels has similar pattern with that of trip time, reflecting daily commuting routines. As can be seen in Figure 5, traffic accidents occur primarily during the daytime and exhibit morning and evening peak times, namely, 7:00–9:00 and 17:00–19:00, which is consistent with trip peak time. Generally speaking, traffic volume during peak hours is significantly higher than at other time periods. To our knowledge, during peak hours, many Chinese travelers tend to adopt high-risk driving behavior in order to reach their destinations on time. Thus,
it is very important to enhance traffic management and dispersions during peak hours.

4. Spatial Distributions of Traffic Accidents

4.1. Accident Frequency. Data on accidents and locations retrieved from the Shanghai Center, 110, were grouped into
the following four categories. From the summary of tunnel traffic accidents, (Figure 6), the accident frequencies of zone 1 and zone 2 are considerably higher than the average. The accident frequency of zone 3 is slightly below the average and that of zone 4 is significantly lower than the average. Thus, it can be seen that accidents occurred primarily in zones 1, 2, and 3 as opposed to being uniform or randomly distributed. The main reasons of this phenomenon are visibility and speed. Generally speaking, when a vehicle enters a tunnel, the driver requires a short time period to adapt to the dim light conditions (also called “black hole’) in the tunnel. Similarly, when the vehicle leaves the tunnel, intense daylight outside the tunnel will lead to a bright “white hole” both of which adversely affect the drivers vision. In addition, according to Zhao et al’s [21] research, when a vehicle approaches a tunnel, the driver normally decelerates as he approaches tunnel entrance. After entering the tunnel, the driver will then accelerate to a speed that is lower than that of an open road. These large speed fluctuations have a deleterious impact on traffic safety.

4.2. Accident Severity Analysis. A total of 203 persons were injured in the 167 injury-related accidents included in this study. The severity of the injuries in each tunnel zone is shown in Figure 7. Most injury-related traffic accidents occur in zone 1 and zone 4 but there were no fatalities in these accidents. In tunnels the share of serious injuries and fatal injuries in all accidents is 2.4%, while this proportion on the open road outside the tunnel is only 1.2%. A similar pattern is also found for the number of injuries per accident, which is 1.26 in tunnels compared with 1.13 on the city roads outside tunnels. Table 1 gives an overview of the number of injuries per accident.

4.3. Accidents versus Weather. We also studied the relationship between weather conditions and accidents. Accidents occurring on rainy days stood at 47.6 percent of total number of accidents. Of accidents occurring within 50 m of the opening sections of tunnels (zones 1 and 2), 38.5% took place on rainy days. In zones 3 and 4 the proportions of accidents happening on rainy days was 23.6% and 27%, respectively.

Presumably, the reason for these results is that road friction near tunnel entrances and exits decreases significantly in wet conditions. On rainy days, vehicles drag significant quantities of rainwater into a tunnel which probably reduces the frictional coefficient of the pavement at the entrance zone, thereby leading to an increase in accident risk. When vehicles leave the tunnel, they travel from a dry surface in the tunnel to a slippery road surface near the tunnel exit. This significant change of road friction could also lead to a higher accident risk.

5. Accident Types

There is a variety of car accidents, including head-on collisions, sideswipes, rear-end collisions, bumping, scrapes, rollovers, and fires. According to the acquired accident data, accidents in tunnels were divided into seven categories: head-on, sideswipe, rear-end, fixed object, rollover, and others. Figure 8 indicates that rear-end accidents account for 80 percent of all accidents while sideswipe accidents account for only 9 percent. We assume that the basis for these data is that the tunnel roads in Shanghai are all one-way roads with high traffic volumes and most accidents involving multiple vehicles are rear-end or side-swipe accidents. In addition,
6. Road Classifications and Traffic Accidents

According to the Code for Transport Planning on Urban Roads [20], urban roads can be divided into the following categories in terms of road functionality: expressway, arterial roads, secondary roads, and slip roads. Traffic volumes and vehicle speed limits vary with the design of the road functionality. Table 2 and Figure 9 give an overview of the relationship between city road classifications and traffic accidents. As can be seen from the figure, most traffic accidents occur on the expressway, accounting for 55 percent of the total, while arterial road and secondary roads account for 24 percent and 21 percent, respectively. At least two fundamental factors appear to contribute to this phenomenon. First, expressway and arterial roads are the traffic arteries of city’s transportation network and, therefore, accommodate a very large volume of traffic. This trend will continue as the proliferation of expressways in Shanghai increases currently stretching to over 192 km in length. These expressways constitute 45 percent of road network turnover value. Second, although expressways incorporate access control to prevent pedestrian and nonmotor vehicles traffic, accident rates in expressway tunnels are quite high. The reason for this could be due to the high design speed and operating speed on expressways. As previously stated, transition zones in tunnels are very dangerous areas. Thus, drivers who are approaching tunnels at high speed are exposed to much higher accident risk.

7. Countermeasures

Based upon the described data analysis, suggestions for improving traffic safety in tunnels in Shanghai can be addressed as follows.

1. Improvement of road surfaces could be an effective way to reduce traffic accidents in tunnels. First, tunnels should be cleaned regularly to ensure that the surface of the road in the tunnel is free from debris, oil, or any foreign matter. Second, proper drainage design and strict quality control of construction should be used to reduce rainwater runoff into tunnels. In addition, skid-resistance pavement could be installed to improve road friction.

2. Traffic control coordinated with traffic guidance can be used as a fundamental method for minimizing tunnel traffic jam problems and help to reduce tunnel traffic accidents. First, installation of variable message signs (VMS) can provide drivers with real-time traffic information so that drivers could change their travel plans when congestions/accidents occur in tunnels. The information on accidents could also warn drivers entering a tunnel to help them avoid secondary accidents. In addition, traffic regulations should be adopted to prohibit high speed vehicle
passing in tunnels. Second, risky driving, aggressive lane change, and speeding are known to be some of the main reasons leading to high accident rates in tunnels. Consequently, establishing reasonable speed limit standards could provide a simple method for controlling risky driving behavior to reduce accidents in tunnels. Third, the presence of large commercial vehicles in tunnels has been shown to cause erratic automobile driving which is directly correlated with traffic accidents. Consequently, traffic regulations should be considered to separate small passenger cars and large vehicles. For example, providing restrictions on large vehicle movement move during certain time periods or restricting them to traveling in designated lanes.

(3) Horizontal alignment should meet the requirements of design consistency. With regard to geometric design of tunnel sections, curves and ramps need to be avoided as much as possible, especially over long and steep downgrade sections. If ramps and curves cannot be avoided, speed bumps should be installed at specific distances away from tunnel entrances to reduce the speed of tunnel entrance.

(4) Lighting conditions in zone 1 and zone 2 need to be carefully designed in order to eliminate the “black hole” condition in tunnel entrances and “white hole” conditions at tunnel exits. This will help to alleviate the number of accidents in zone 1 and zone 2 which are considerably higher than in other areas. The tunnel lighting system that is recommended should include entrance section lighting, transition section lighting, the basic lighting of middle section, exit section lighting, and emergency lighting. For the entrance zone of a tunnel, the recommended lighting should start with yellow lights and gradually change to daylight lamps. Such a layout of illumination may help drivers to adapt to the tunnel environment and reduce the effects of “black hole” and “white hole.”

8. Conclusion
Patterns of city life and daily commuting exert a major impact on the distribution of traffic accidents in roadway tunnels. Data have shown that the highest incidents of traffic accidents occur on Monday and Friday and the number of traffic accidents on weekends is much lower than on weekdays. The hourly distribution of traffic accidents in tunnels reveals that traffic accidents occur mainly during the daytime and are most significantly during morning and evening peak times, namely, 7:30–9:30 and 16:30–18:30. Most traffic accidents occur in zone 1, zone 2, and zone 3 in tunnels. The number of traffic accidents near entrances and exits (at zones 1 and 4) are significantly higher than in other tunnel zones. Most injury-related accidents occur in zone 1 and zone 4 but did not result in fatalities. The share of accidents that occurred on rainy day was found to be as much as 47.6% of the overall total number of accidents.

Rear end collisions represent the major type of accident in tunnels. Of the total number of accidents, rear end collisions accounted for the highest percentage among all the accident types, reaching 80%. This is probably due to the failure to maintain a safe distance between vehicles in the tunnel.

The majority of traffic accidents in tunnels resulted from high speed travel (80 km/h or more), possibly due to high speed, heavy traffic volume, and the confined space of the tunnel. It should be noted that the analysis in this paper resulted from a search for the accident patterns rather than a prediction of accident frequency. The analysis of tunnel accidents and related factors may provide a better understanding of tunnel accident risks and the information needed to establish effective safety countermeasures. The safety countermeasures suggested in this paper can be used as a reference for traffic safety improvements for traffic tunnels in Shanghai.

Conflict of Interests
The authors declare that there is no conflict of interests regarding the publication of this paper.

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