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Safety Analysis of Urban River-crossing Tunnels Based on VISSIM

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Abstract

The safety of river-crossing tunnels is an important aspect of urban road traffic systems. Previous studies concerning traffic safety mainly focused on urban roads. Given the absence of a number of variables, such as speed and real-time traffic volume, in traffic accident databases, the traffic safety of urban river-crossing tunnels has rarely been studied. This study used the microscopic traffic flow simulation software, VISSIM, to analyse the factors influencing the traffic safety of urban river-crossing tunnels. 12 simulation models based on 12 river-crossing tunnels in Shanghai were established. An exponential model for the speed standard deviation and accident rate was then constructed by calculating the speed standard deviation of the 12 tunnel models. Varied parameters of gratitude, speed limit, heavy vehicle ratio, and traffic flow characteristics were used to set different simulation scenarios in VISSIM. Results show that speed standard deviation is negatively correlated with gradient and heavy vehicle ratio, where a smaller gradient and fewer heavy vehicles are safer. Under different traffic volumes, the speed standard deviation first increases and then decreases with the increasing speed limit. From the perspective of traffic safety, a small speed limit is recommended; however, the number of passing vehicles per hour is reduced. Thus, a middle speed limit between 55 km/h and 60 km/h is recommended to balance the safety and efficiency of traffic. The findings in this study provide prospective information with which to optimize the design and operation of urban river-crossing tunnels.

Keywords: Urban river-crossing tunnels, Accident rate, Speed standard deviation, VISSIM

1. Introduction

Traffic safety is a major concern worldwide. Almost 1.25 million people died from road accidents in 2013 (WHO, 2015). Therefore, identifying the factors that affect traffic safety is a meaningful research topic. Previous studies showed that analyzing traffic accident databases is simple and useful in evaluating the factors that affect traffic safety. However, traffic accident data is sometimes insufficient or incomplete. Simulation is widely adapted in traffic network analysis, evaluation, and optimization, and the comparison of designs，which is likewise an effective tool to analyze traffic problems [1]. In existing literature, the analysis of traffic safety has focused on urban roads, especially intersections [2].

With the development of economy and society, numerous river-crossing tunnels and bridges have been built along river cities, such as London, Paris, and Seoul, to meet the increasing traffic needs of residents. However, compared with open roads and bridges, river-crossing tunnels impose a unique form of driving behavior. Drivers must adapt to the change of light when passing in and out of the river-crossing tunnels, which results to the "black hole" and "white hole" effect. The severity of an accident happening in a tunnel is usually greater than occur along open stretches of freeways [3]. In Shanghai China, the percentage of serious injuries and fatal crashes in river-crossing tunnels is twice that of open roadways.

The focus of this study is to determine the influence of various factors, such as the gradient, speed limit, and heavy vehicle ratio, on the traffic safety of urban river-crossing tunnels. This study utilizes different simulation scenarios in VISSIM software. Speed standard deviation is selected as an index to measure traffic safety based on the correlation between the speed standard deviation and accident rate of the 12 river-crossing tunnels in Shanghai.

2. State of the art

Two methods are primarily used in traffic safety assessment: direct and indirect safety evaluation. In direct safety evaluation, the expected value of the traffic accident rate based on the previous statistical data of traffic accidents is used as an evaluation index. Girottoa et al. conducted a cross-sectional study wherein truck drivers were interviewed regarding their sociodemographic characteristics, working conditions, behavior in traffic, and involvement in accidents or near-miss accidents in the previous 12 months [4]. They presented certain studies about a number of roads in the Republic of Macedonia to express the functional dependence of the dynamic homogeneity on the number of road accidents in urban areas. Ognjenovic et al. discussed the relationship between accident rate and dynamic homogeneity obtained from the construction of the velocity in free traffic flow; this relationship served as reference to newly designed and already constructed roads [5]. However,

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the acquisition of accident data is difficult and time-consuming. Data records are sometimes incomplete, which limits the use of this method.

Traffic simulation technology is an indirect safety assessment method that is widely applied in studying intersections. Huanyun Zhou and Fei Huang found that the simulated conflicts generated by VISSIM and identified by Surrogate Safety Assessment Model were decreased after reducing the speed limit at signalized intersections [6]. Sayed et al. studied traffic conflicts as critical-event traffic situations as well as the effect of driver and traffic parameters, such as volume and speed, on the occurrence of conflicts at un-signalized intersections [7]. This simulation method does not require long-term historical accident data and can conduct rapid, pre-defined traffic safety assessments of planned transport facilities.

The factors affecting traffic safety are generally divided into two categories: engineering factors and human factors. Engineering factors include road infrastructure characteristics, traffic conditions, and ambient conditions. Human factors include characteristics such as their blood-alcohol level [8]. Heavy goods vehicle drivers are in the high-risk group [9]. Many studies have focused on the relationship between traffic accidents and geometric design variables, such as curvature, vertical grade, lane width, and hard-shoulder width [9, 10]. Tarek Sayed and Emanuele Sacchi performed a before–after evaluation with a full Bayesian technique, which showed that changing the speed limit significantly increases fatal-plus-injury (severe) crashes on rural highways by 11.1% [12]. Longitudinal gradient, speed limit, traffic flow, and traffic composition are considered in this study.

A few studies have focused on the field of urban river-crossing tunnels. Lu et al. analyzed the temporal and spatial distribution characteristics of traffic accidents of urban river-crossing tunnels [13]. Jiang et al. analyzed single-vehicle crash injury severities and hit-and-run crashes in urban river-crossing tunnels [14, 15]. These studies focused on analyzing accidents in urban river-crossing tunnels. However, considering the absence of a number of variables, such as speed and real-time traffic volume, in the traffic accident database, the influence of different designs and operational situations on the occurrence of traffic accidents requires further study. The present study uses VISSIM software to simulate urban river-crossing tunnel models and subsequently identify several traffic variables as a reference. The variables are used to determine the relationships between the longitudinal gradient, speed limit, traffic flow, traffic composition, and traffic safety.

This study is organized as follows. In Section 3, 12 river-crossing tunnel models of Shanghai are established, and the speed standard deviation of each tunnel is calculated to propose an exponential model of the speed standard deviation and accident rate of urban river-crossing tunnels. Section 4 discusses the influence of various factors, such as gradient, speed limit, and heavy vehicle ratio on speed standard deviation. Section 5 contains the summary of the conclusions.

3. Methodology

3.1 Basic data collection

3.1.1 Accident data collection

Accident data of 12 crossing-river tunnels derived from the Official Platform of ‘110’ Alarming Receiving Centering (OP110ARC) of the Shanghai Public Security Bureau in 2011 were used to calculate the accident rate of each tunnel. Table 1 shows the calculated annual average daily traffic (AADT), which is the total traffic volume of the tunnel in a year divided by 365 days. The traffic volume was measured in terms of passenger car unit (pcu). The accident rate is the number of accidents occurring in or around the tunnel per million vehicle-kilometers in a year.

Table 1. Accident rate of 12 river-crossing tunnels in Shanghai in 2011

	Accident number in 2011	**Length (m)**	**AADT (pcu/d)**	**Accident rate**
Dapulu Tunnel	201	2761	31000	6.43
Dalianlu Tunnel	151	2527	43000	3.81
Fuxingdonglu Tunnel	136	2780	46000	2.91
Jungonglu Tunnel	408	3050	24000	15.27
Longyaolu Tunnel	87	3564	19000	3.52
Renminlu Tunnel	77	3097	24000	2.84
Shangzhonglu Tunnel	250	2800	70000	3.49
Waihuan Tunnel	2277	2880	68000	31.85
Xizangnanlu Tunnel	90	2670	21000	4.40
Xiangyinlu Tunnel	1444	2606	79000	19.21
Xinjianlu Tunnel	172	2235	22000	9.58
Yan’andonglu Tunnel	909	2261	88000	12.52

3.1.2 Simulation data collection

VISSIM was developed by PTV and is a common microscopic traffic flow simulation software. The Wiedemann 74 car following model was used to build the models of urban river-crossing tunnels. Considering the “black hole” effect, the driver needs to adapt to the drastic changes of brightness upon entering and exiting a tunnel (Figure 1). The entrance of an urban river-crossing tunnel is downhill; hence, the deceleration starts when the driver approaches the entrance of the tunnel. According to Chen’s analysis of the entrance section of mountain expressway tunnels, Point A is the adapting point where the driver begins to decelerate [16]. Point P is the entrance of the tunnel. Deceleration ends at Point B. According to the provisions of “Design Code for Road Tunnels” (DG-TJ08-2033-2008) (Shanghai), the longitudinal gradient is -3%, the clearance height of the opening is 4.5 m, and the designed speed is 40 km/h. The adaptation distance d is 17.01 m, D_{th} is 14.14 m, and the total deceleration distance is 31.15 m. In this study, all vehicles were set to decelerate in the AB segment (31 m) in VISSIM through the deceleration zone and expected speed decision point.

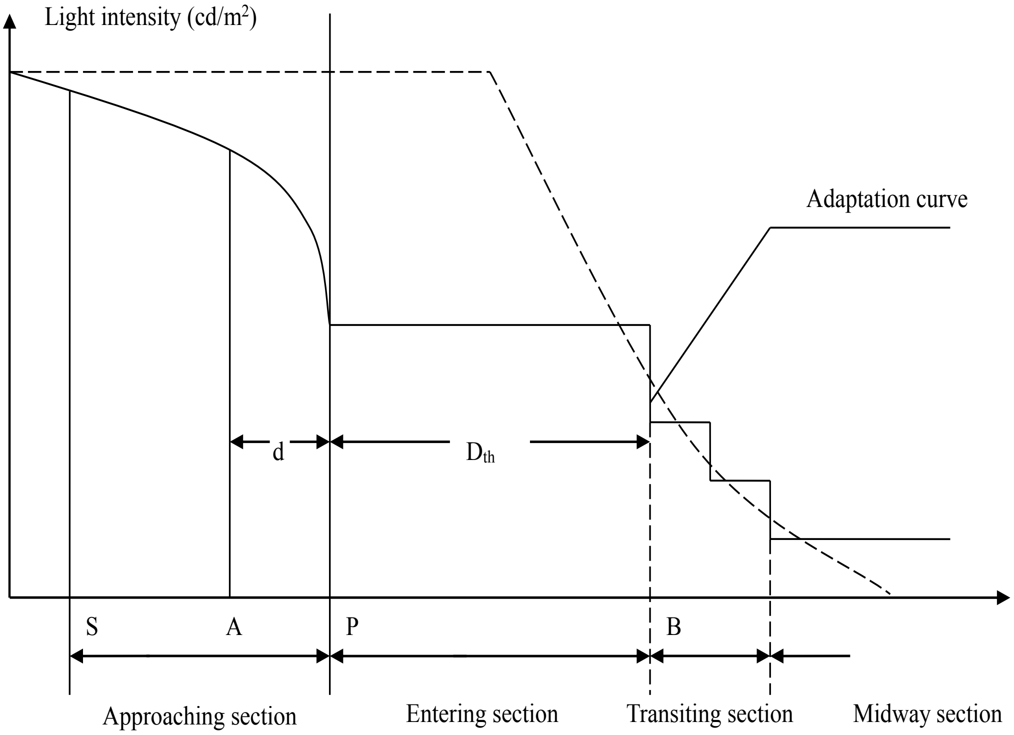

Fig. 1. Process of a vehicle to the tunnel

The 12 river-crossing tunnel models of Shanghai were established according to the geometric features, traffic flow, traffic compositions, and speed distributions of each tunnel by VISSIM. A typical model of the Longyaolu Tunnel is displayed in Figure 2. Data collecting points were set every 100 meters, and the speed standard deviations of 12 tunnels were calculated through the output data.

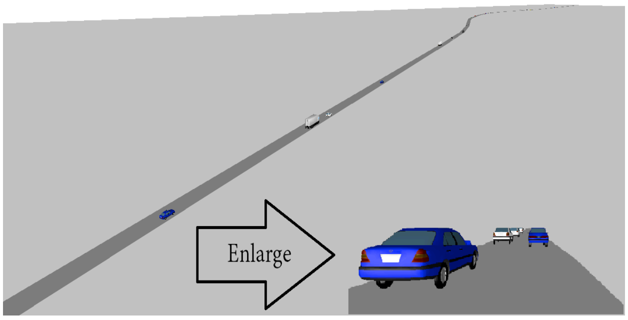

Fig. 2. Model of Longyaolu Tunnel in VISSIM (west to east direction)

3.2 Accident rate model

Figure 3 shows the positive correlation between speed standard deviation and accident rate. The exponential relationship observed between speed standard deviation and accident rate is as follows:

$$AR = 1.5077e^{2.0429\sigma} \tag{1}$$

where AR is the accident rate and σ is the speed standard deviation (km/h).

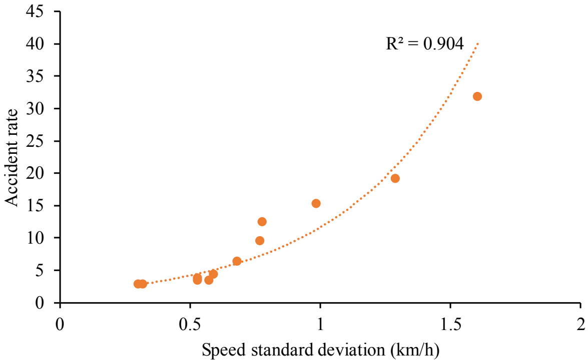

Fig. 3. Relationship between speed standard deviation and accident rate

When the speed standard deviation descends to zero and all vehicles travel at the same speed, the accident rate is approximately 1.5077, which indicates that the occurrence of an accident is not only related to speed. As a result of the vehicle performance and speed limit, the speed standard deviation is limited within a certain range. Therefore, the accident rate is not infinitely increased. This model provides a theoretical basis for the design and management of urban river-crossing tunnels.

3.3 Design of simulation scenarios

Various parameters, including gratitude, speed limit, heavy vehicle ratio, and traffic flow characteristics were used to create different simulation scenarios in VISSIM. All river-crossing tunnels built in Shanghai are double-hole, and mostly contain two lanes in each direction. River-crossing tunnels are connected with urban roads; hence, the width is set at 3.5 m per lane. A typical two-lane tunnel model based on the linear profile data of 12 river-crossing tunnels in Shanghai is built and shown Figure 4.

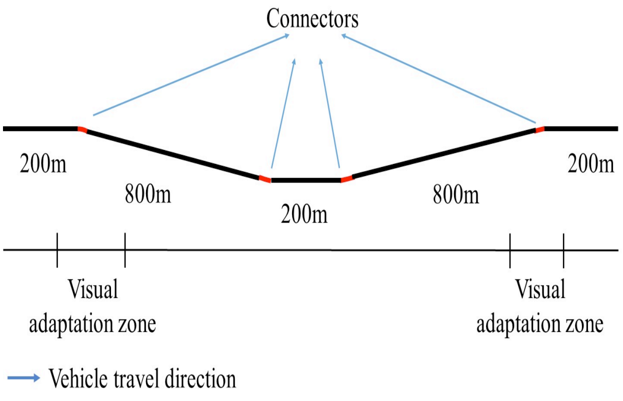

Fig. 4. A typical profile form of urban river-crossing tunnels

4 Result analysis and Discussions

With reference to the current situation of Shanghai, this study mainly analyzed the influence of the longitudinal gradient, from 2% to 6% at increments of 0.5%, on the speed standard deviation under the traffic volume of 1500 vehicles per hour (vph), the speed limit of 40 km/h, and the heavy vehicle ratio of 10%.

For each simulation scenario, the output of VISSIM is 10 speed files from 44 data collecting points. The mean speed standard deviation values in the downhill and uphill sections are shown in Figures 5 and 6.

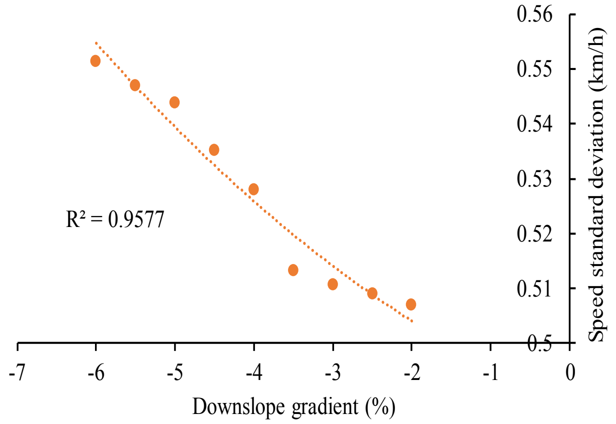

Fig. 5. Relationship between downslope gradient and speed standard deviation

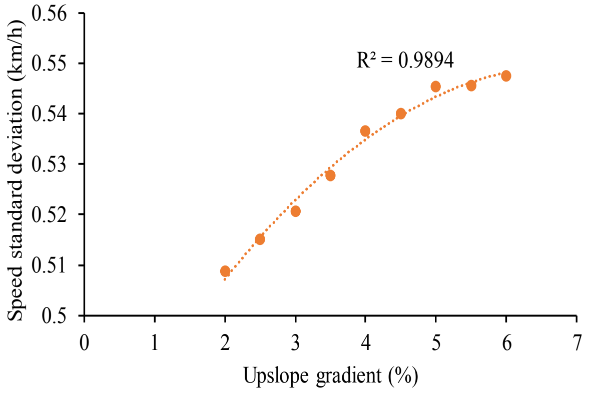

Fig. 6. Relationship between upslope gradient and speed standard deviation

The relationship between gradient and speed standard deviation is expressed as follows:

for the downhill slope,

$$\sigma = 0.0009x^2 - 0.0057x + 0.4892 \quad (2)$$

for the uphill slope,

$$\sigma = -0.0018x^2 + 0.0247x + 0.465 \quad (3)$$

where x is the gradient (%).

The speed standard deviation increases when the absolute value of gradient increases in both downhill and uphill slopes. When the absolute value of gradient ranges from 2% to 3.5%, the effect of the uphill slope on speed standard deviation is greater than that of the downhill slope. When the gradient is between 3.5% and 6%, the effect of the downhill slope is greater than that of the uphill slope. This result is similar with Pei and Cheng's research, which shows that when the gradient is small, the accident rate of uphill slopes is basically similar to that of downhill slopes; however, the accident rate of downhill slopes rapidly increases when the gradient increases [17].

The speed standard deviations under different speed limits when the two-lane traffic volume changed from 500 vph to 3000 vph at an increment of 500 vph were analyzed. Figure 7 shows that when the speed limit is 40 km/h, the speed standard deviation is the smallest. The speed standard deviation also increases with the increasing speed limit; however, the speed standard deviation is reduced when the speed limit reaches 50 km/h. The interval minimum occurs when the speed limit is 65 km/h. This phenomenon occurs because when the speed limit is low, the average speed is low and the speed distribution is concentrated. When the speed limit increases, the speed standard deviation gradually increases. When the speed limit continuously increases to the 85th percentile speed, the speed standard deviation is the interval minimum, which is an ideal value of the speed limit.

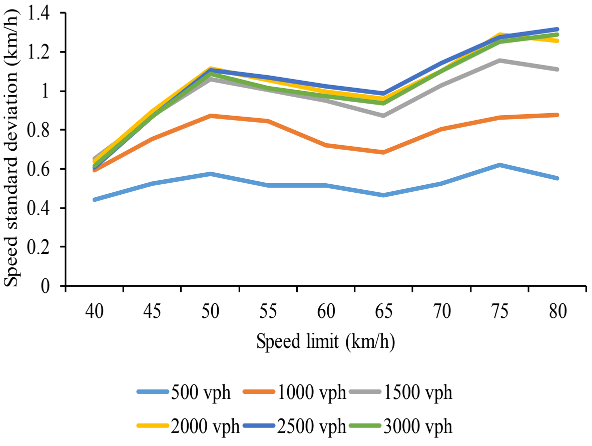

Fig. 7. Relationship between speed limit and speed standard deviation

In general conditions, heavy vehicles cannot keep up with the cars and are forced to form a non-continuous and discrete traffic flow because of their difference in performance and size. The sight of car drivers is blocked when following heavy vehicles, which easily leads to traffic accidents. This study mainly discusses the correlation of the heavy vehicle ratio (from 0% to 20%) with the speed standard deviation. Figure 8 shows that the speed standard deviation increases with the increase of the heavy vehicle ratio; however, the change is not significant.

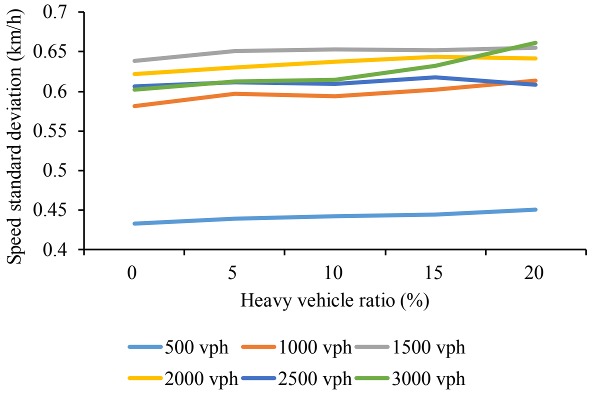

Fig. 8. Relationship between speed standard deviation and heavy vehicle ratio

Figure 7 and 8 show that when the traffic volume is small, the speed standard deviation is low. This phenomenon occurs because the interval spacing is long and the interference between vehicles is small under this condition; most drivers drive in a relatively safe and stable speed range. As the traffic volume increases, the drivers start to consider their interactions with other vehicles; thus, the speed standard deviation increases substantially. However, when the traffic volume continuously increases to a certain extent, most vehicles follow the vehicle in front to form a stable flow. Subsequently, overtaking becomes difficult, and speed standard deviation decreases. The further increase of traffic volume leads to an unstable flow. The risk of overtaking increases, and the speed standard deviation relatively grows. If the volume of traffic increases further, then traffic jams occur, and the speed standard deviation decreases.

5. Conclusions

To analyze the traffic safety of urban river-crossing tunnels, an exponential correlation between speed standard deviation and accident rate was developed based on the simulation models of 12 urban river-crossing tunnels in Shanghai by VISSIM. Different simulation scenarios were created to evaluate the influence of gratitude, speed limit, heavy vehicle ratio, and traffic volume on speed standard deviation. The following conclusions were drawn:

(1) Speed standard deviation is negatively correlated with the absolute value of gradient. Thus, the gradient of urban river-crossing tunnels should be as small as possible to increase traffic safety. Its proposed value should be between 2% and 4%. This value will reduce the difficulties in driving and maintain the necessary speed to increase the travel safety.

(2) In different traffic volumes, the speed standard deviation first increases and then decreases with the increase of the speed limit. A small speed limit between 40 km/h and 45 km/h is recommended for traffic safety purposes. In this situation, the number of vehicles passing through each hour will be reduced; however, the traffic will also be relatively safe when the speed limit is between 55 km/h and 60 km/h. This finding suggests that the speed limit of urban river-crossing tunnels can be dynamically adjusted to the changes in traffic flow. For example, in the morning and evening peaks, the speed limit value can be set to 55 km/h to 60 km/h, whereas in off-peak hours, the limit can be set as 40 km/h. This condition will maximize traffic efficiency and safety.

(3) As the proportion of large vehicles increases, the speed distribution becomes more discrete, and the speed standard deviation increases. Given these circumstances, a larger traffic volume will induce more traffic accidents. In practice, heavy vehicle restrictions in peak hours can be introduced, that is, heavy vehicles should be banned from traveling in urban river-crossing tunnels in the morning and evening peak on weekdays.

In summary, this study provides several recommendations that can be applied in the design and operation stage to increase traffic safety. However, actual vehicle experiments should be conducted to verify the relationship between the speed standard deviation and accident rate. Moreover, traffic safety is influenced by many factors. This study is limited to considering the effect of gratitude, speed limit, heavy vehicle ration, and traffic volume. Additional influencing factors should be considered in future studies.

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