Study on the Standard of Fire Disaster Prevention for Super Large Cross Section Immersed Tunnels

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Abstract. Relying on the Shenzhen-Zhongshan subsea immersed tunnel project, combined the characteristics of highway tunnel traffic, the method of fire standard for super large cross section submarine immersed tunnel is proposed. Through the analysis of road tunnel fire cases, it is clear that vehicle spontaneous combustion is the main cause of tunnel fires. The ignition distance of different fire scales under the condition of tunnel traffic jam is determined by theoretical calculation. Through numerical simulation, when a super large cross section submarine immersed tunnel is fired under the condition of traffic jam, the scale of the fire is enlarged due to the ignition of the vehicle, and the fire scale design value of the super-large cross section submarine immersed tunnel is obtained. Based on the most dangerous situation of vehicle spontaneous combustion in an uni-direction four-lane tunnel, according to the actual traffic composition, the probabilistic method is used to analyze the composition of the laterally ignited vehicle and the probability of the event. It shows that the maximum probability of being ignited in a four-lane tunnel is one coach and one truck, and the fire prevention standard for Shenzhen-Zhongshan immersed tunnel is determined to be 50MW.

1. Introduction
In recent years, more and more immersed tunnels have been built at home and abroad. The immersed tunnel is in an underwater environment, which puts forward more stringent requirements for safety during operation under fire conditions due to its special structure [1]. The tunnel fire prevention standard is the basis of the tunnel safety design, which is great significance to the tunnel ventilation system design, escape channel design, structural fire protection design, equipment fire performance design, tunnel repair and maintenance.

The determination of fire prevention standards is very important in the fire protection design of tunnel engineering, which is an essential part in fire protection design. Fire prevention standards are the basis for developing prevention strategies, designing fire prevention systems, selecting fire protection equipment, and carrying out related work. The materials burning in road tunnel fires mainly come from vehicles that are involved in combustion, including loaded combustible goods, fuel and vehicle accessories. The tunnel itself is less involved in the combustion of combustible materials, so the combustion heat release energy of the vehicle and the loaded cargo is usually used as the basis for the classification of fire protection standards [2].

Many research institutes and scholars have studied the combustion behavior and fire scale of different types of vehicles through full-scale experiments and obtained the fire scale of different types of vehicles [3, 4]. Urban traffic is dominated by small cars and has the characteristics of tidal traffic.
During the morning and evening traffic peaks, the traffic in urban tunnels is slow, and the vehicle spacing is small, which is extremely prone to traffic jams. The tunnel space is narrowly closed with the poor conditions of evacuation and the high density of fire load. Under the condition of tunnel fire, it is likely to cause heat accumulation and a sharp rise in internal temperature, and the scale of fire will be increased by the igniting of surrounding vehicles [5].

At present, the maximum fire scale of various types of vehicles passing through the tunnel is generally determined to the scale of the fire. Through the case of tunnel fires at home and abroad, the scale of fire determined according to the above method is often too small. This paper relied on the Shenzhen-Zhongshan immersed tunnel project to study the fire prevention standards for super large cross section immersed tunnels, and provide reference for tunnel fire rescue.

2. Analysis of Fire Characteristics in Highway Tunnels

The World Road Association research report "Road Tunnel Fire and Flue Gas Control" (1999) pointed out that road tunnel fires usually involve traffic vehicles, mainly caused by circuit failure, overheating of brake system, and other malfunction caused spontaneous combustion of the vehicle. Vehicle crash, malfunction of mechanical and electrical equipment is also the reason for road tunnel fires, but the frequency is usually low. In theory, the frequency of road tunnel fires is related to tunnel length, traffic volume, design speed and the line characteristics of road [6].

In recent years, the number, scale and length of road tunnels in China have been increased. However, road tunnels have brought convenience with the risk of fire increased. The safety of road tunnels has been received more and more attention. In order to grasp the main causes and laws of tunnel fires from a macro perspective, some cases of road tunnel fire accidents occurred in China were analyzed, as shown in Figure 1.

It can be seen from Figure 1 that the tunnel fire accounted for the largest proportion due to the vehicle itself, which is 52%. These fire accidents include 14 fires caused by engine failures, 17 fires on the tires, 5 fires caused by electrical circuits, and 16 other forms of spontaneous combustion. The proportion of tunnel fire accidents caused by the impact is also relatively large, which is 29%, including 23 fire accidents caused by vehicle collisions, 4 fires caused by bicycle impact on the tunnel wall, and 2 fires caused by collision with the road after the vehicle turns over. There were 7 fires caused by spontaneous combustion of the goods, accounting for 7%. It is shown that the main cause of the tunnel fire is the vehicle self-igniting due to the failure of the vehicle itself.

3. Fire ignition distance of vehicle

When a vehicle in the tunnel burned, the radiant heat of the adjacent vehicle reaches and exceeds the critical heat flux of the approaching vehicle, the adjacent vehicle will be ignited. The heat of the vehicle adjacent to the burning vehicle is mainly derived from the high temperature flame generated by the burning of the burning vehicle and the heat of the smoke [7].

Figure 1. The cause of highway tunnel fire
3.1. The ignition distance of fire radiation
The heating of vehicles adjacent to a vehicle in question comes from three basic forms, namely heat conduction, heat convection and heat radiation. The heat that ignites adjacent vehicles is mainly due to the heat radiation of the vehicle (\(I_{\text{flame}}\)) and the radiation of the hot smoke (\(I_{\text{smoke}}\)). When the sum of the radiant heat flux exceeds the critical radiant heat flux (\(I_C\)) of the vehicle’s ignition, the vehicle will be ignited. Therefore, the critical conditions for ensuring that adjacent vehicles are not ignited is:

\[ I_{\text{flame}} + I_{\text{smoke}} < I_C \]  

(1)

Some of the heat released by the fire vehicle will radiate outward in the form of radiation. The relationship between the fire source radiation and the heat release rate of the fire source received by the adjacent car at the heart of the fire source is:

\[ I = \frac{Q}{12\pi x^2} \]  

(2)

\[ I_{\text{smoke}} = F_S \varepsilon_S \sigma T_S^4 \]  

(3)

where \(I\) is the radiant heat received by the adjacent car, kW/m\(^2\); \(Q\) is the heat release rate of the fire, kW; \(I_{\text{smoke}}\) is the radiant heat flux of the smoke generated by the burning vehicle to the adjacent vehicle, kW/m\(^2\); \(x\) is the distance from the center of the burned car to the surface of the adjacent car, m; \(\varepsilon_S\) is the radiation of the smoke layer; \(\sigma\) is the Stephen-Boltzmann constant, kW/(m\(^2\)·K\(^4\)); \(T_S\) is the temperature of the smoke layer, K.

The fire radiation ignition distance is:

\[ x = \sqrt[3]{\frac{Q}{12\pi I}} \]  

(4)

The relationship between the scale of the fire and the ignition distance is shown in Figure 2.

3.2. Ignition distance of smoke layer radiation
In an infinite smoke layer with a constant temperature, the radiation is generated by temperature and can be expressed as:

\[ E_r = 5.67 \times 10^{-8} \times \varepsilon_r \times T_4 \quad (w / m^2) \]  

(5)
where $\varepsilon_r$ is the emissivity, 0.8; $T$ is the temperature of fire smoke, K.

Most automobiles are coated with a thermoplastic material such as polyurethane. Therefore, the critical heat flux for ignition can be 16 kW/m$^2$. That is, the temperature of the fire smoke reached 771 K, which will ignite the surrounding vehicles. The distance from the point of the fire source at a temperature of 498 °C is the radiation ignition distance of the fire smoke layer.

The scale of tunnel fires used in countries around the world varies greatly. The scale of tunnel fires considering heavy trucks is 20~200 MW. Among them, the fire scale recommended by NFPA502 in the 2004 edition is 20~30 MW. After using relevant experimental data, the recommended fire prevention standard after the 2008 edition is 70~200MW. In general, the heat release rate of a stable combustion phase of different types of vehicles is shown in Table 1.

Table 1. Heat release rate during stable combustion stages of different vehicles

| Vehicle type         | Car | Van | Truck or bus | Tank truck | Big tank truck |
|----------------------|-----|-----|--------------|------------|---------------|
| HRR (MW)             | 3~5 | 10  | 20           | 50         | 100           |

At present, the curves of temperature versus time which are more common at home and abroad mainly include ISO curve, hydrocarbon curve, RWS curve and RABT curve [8]. The main structure design needs to consider the maximum temperature and fire resistance time according to the temperature curve. At the same time, it is necessary to consider the fire resistance of the secondary structure such as the smoke exhausting channel.

According to the maximum temperature of various types of vehicle fires provided in the PIARC report, when the fire source is a small car, the maximum temperature at the fire source is about 200 °C. When the fire source is a medium-sized car, the maximum temperature at the fire source is about 500 °C. When the fire source is a coach, the maximum temperature at the fire source is about 800 °C. As shown in Figure 3.

![Figure 3. Relationship between time and standard temperature](image)

The critical temperature of the fire smoke surrounding the vehicle is 498 °C, so the ignition distance of the smoke and smoke layers of small cars and medium-sized cars is 0. In the case of full combustion, the ignition distance of large passenger coach is 8m. The ignition distances under different fire scales are shown in Table 2.
Table 2. Ignition distance under different fire scale

| Fire scale (MW) | 2.5 | 5   | 20  |
|----------------|-----|-----|-----|
| Ignition distance (m) | 2.0 | 2.9 | 8   |

3.3. Fire protection standards of typical tunnel projects at home and abroad

The fire protection standards of typical tunnel engineering at home and abroad are shown in Table 3. Most tunnels clearly stipulate that dangerous goods transport vehicles are not allowed to pass, and the maximum heat release rate of fires is reduced effectively.

Table 3. Fire protection standards of typical underwater tunnel engineering

| Tunnel                             | HHR (MW) | Tunnel length (km) | Tunnel characteristics     |
|-----------------------------------|----------|--------------------|-----------------------------|
| Shanghai Yangtze River Tunnel     | 50       | 8.95               | Dual-directional 6-lane     |
| Nanjing Yangtze River Tunnel      | 50       | 6.04               | Dual-directional 6-lane     |
| Wuhan Yangtze River Tunnel        | 50       | 3.63               | Dual-directional 4-lane     |
| Xiamen Xiang’an Subsea Tunnel     | 20       | 8.695              | Dual-directional 6-lane     |
| Qingdao Jiaozhou Bay Subsea Tunnel| 20       | 7.8                | Dual-directional 6-lane     |
| Qianjiang tunnel                  | 50       | 4.45               | Dual-directional 6-lane     |
| Tokyo Bay Subsea Tunnel           | 50       | 9.5                | Dual-directional 4-lane     |
| Hong Kong-Zhuhai-Macao immersed   | 50       | 6.25               | Dual-directional 6-lane     |
| tunnel                            |          |                    |                             |

4. Evacuation time

Personnel evacuation is the standard for determining the scale of fires, that is, the scale of fires that the total number of vehicles ignited by fire vehicles reaches within the time when personnel evacuation is completed.

4.1. Analysis of vehicle parameters in tunnel

When determining the fire prevention standard of a tunnel fire, consider the scale of the fire in the case of a tunnel jam. In the case of traffic jams, the longitudinal and lateral spacing of adjacent vehicles in the tunnel is an important factor affecting whether the vehicle is ignited by fire vehicles. According to previous research results, the longitudinal spacing of vehicles in the tunnel is 1m [9]. The outer contour of the vehicle in the road tunnel is shown in Table 4.

Table 4. Outer contour dimensions of vehicle

| Type of vehicle | Total length (m) | Total width (m) | Total height (m) |
|-----------------|------------------|-----------------|------------------|
| Car             | 6                | 1.8             | 2                |
| Bus             | 13.7             | 2.55            | 4                |
| Articulated bus | 18               | 2.5             | 4                |

Assumed that the vehicle is located in the middle of the lane, taking the Shenzhen-Zhongshan immersed tunnel project as an example. According to the design data, the lane width is 3.75m, and the lateral spacing between adjacent sides of each type of vehicle is shown in Table 5.
Table 5. Transverse spacing between different types of vehicles (m)

| Transverse spacing | Car  | Medium bus | Coach |
|--------------------|------|------------|-------|
| Car                | 1.7  | 1.3        | 1.35  |
| Medium bus         | 1.3  | 0.95       | 1     |
| Coach              | 0.35 | 1          | 1     |

4.2. Evacuation speed
The speed at which people evacuate in a fire tunnel is mainly related to the age of the person, the visibility in the tunnel, and the unevenness of the road surface. Adults are evacuated at a speed of 1m/s to 1.2m/s in a well-lit environment with a flat surface. The velocity distribution in different categories of people uses a uniform distribution pattern, as shown in Table 6.

Table 6. Evacuation speed of different types of personal

| Type of personal | Child | Adult male | Adult female | Elderly |
|------------------|-------|------------|--------------|---------|
| Evacuation speed | 0.67  | 1          | 0.8          | 0.6     |

4.3. Number and composition of personnel
According to the survey of the permitted number of passengers of various types of vehicles, the number of passengers allowed for small passenger cars is 5, that of passenger cars is 20, and that of big coach is 40. The proportion of people of different genders and ages is shown in Figure 4:

4.4. Evacuation calculation
According to the analysis of the vehicle type and the composition of the personnel, the total number of people to be evacuated within the range of 580m is 1,703. Combined with the actual situation of the Shenzhen-Zhongshan immersed tunnel, the distance between the escape doors in the tunnel is 82m and the width is 1.2m. It is assumed that the fire occurs at the escape door, which is the most dangerous situation, and the evacuation calculation model is established. The calculation model is shown in Figure 5.
The total evacuation time includes fire detection and warning time, personnel response time, and moving time [10]. After the fire broke out, when the fire warning and personnel response were completed, the personnel began to escape. The end of evacuation is the time when the last person entered the cross channel. After calculation, the total evacuation time was 388s.

5. Determination of fire protection standards

Considering the ignition distance of different types of vehicles, the car cannot ignite adjacent vehicles during the evacuation time of the personnel, and the coach can ignite the lateral vehicles.

The dangerous goods vehicles are prohibited in the Shenzhen-Zhongshan immersed tunnel. The types and positions of the vehicles in the tunnel are randomly distributed. According to the actual traffic composition ratio, the probability composition and the event probability of the vehicle are compared. From the calculation result of the probability of occurrence of the event, the probability that the piloted vehicle in the four-lane tunnel is composed of one large truck and one large coach is relatively high. The probability of which is 0.81, and the fire scale was about 43.5MW. The proportion of ignition vehicles in other vehicles is relatively small. In the actual fire protection design, when a certain safety margin is taken, the 50MW fire can be used as the fire prevention standard for the Shenzhen-Zhongshan immersed tunnel.

At present, the automatic fire extinguishing system used in the tunnel takes only 3 minutes from the occurrence of a fire to the automatic operation of the automatic fire extinguishing system [11]. According to the analysis results of the tunnel fire development process, in the case of the ban on the passage of hazardous chemicals vehicles, the heavy trucks transporting ordinary goods such as plastics, rubber, paper products, timber, etc., even if the peak fire scale may reach 200 MW, within 3 to 4 minutes after the fire, the actual fire scale is still within 50 MW.

Combined with the analysis of the control effect of fire facilities on the scale of the fire, through the fire automatic alarm system and the automatic fire extinguishing system were used effectively, it can be considered that the tunnel fire can be controlled within 50 MW in a timely and effectively way during the tunnel operation.

6. Conclusions

The design of the fire scene is the basis for the safety design of the submarine immersed tunnel, which is the guarantee for the safe operation of the tunnel. Through engineering case investigation, combined with the actual characteristics of the project, this paper carries out numerical simulation calculation and probability analysis. The fire prevention standards for the super large cross section Shenzhen-Zhongshan immersed tunnel was determined. The following conclusions are drawn:

(1) Through the analysis of the causes of fire accidents in highway tunnels, it is indicated that the main cause of tunnel fires is the self-ignition of vehicles due to the malfunction of the vehicle itself.

(2) The relationship between the fire scale and the ignition distance of the fire source is obtained by theoretical calculation of the ignition distance of the fire source. According to the calculation formula of the heat flux of the fire smoke layer, the distance from the fire source at a temperature of 498°C is the radiation ignition distance of the fire smoke layer. In the case of full combustion, the ignition distance of a big coach is 8m.

(3) The probability of ignited vehicle in a four-lane tunnel is composed of a truck and a big coach is relatively high, which is 0.81, and which of other vehicle components is relatively low.

(4) In the case of prohibiting the passage of hazardous chemicals vehicles in Shenzhen-Zhongshan immersed tunnel, through theoretical analysis, numerical simulation, engineering investigation, and
combined with the control effect of fire facilities on the scale of fire, the fire prevention standard for the Shenzhen-Zhongshan immersed tunnel is determined to be 50MW.

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