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Study on Fire Accidents in Tunnels

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Abstract: This paper provides a collection of information on 156 tunnel fire accidents at home and abroad and analysis of their time and spatial distribution, accident causes and effects. The study shows: most tunnel fires occur in summer; tunnel fire accidents are frequent in economically developed areas of eastern and southern China as well as mountainous areas in southwestern and northwestern China; long tunnels and super long tunnels experience more fire accidents which occur mostly at tunnel entrance/exit; most tunnel fires are caused by spontaneous combustion of vehicles and traffic accidents; cars and trucks are the most frequently seen models in tunnel fires; consequences of tunnel fires include casualties, vehicle damage, damages to tunnel structure and facilities and traffic interruption. At the end of the paper, appropriate measures and advice are proposed for tunnel fire accidents based on the above analysis results.

1. Introduction

Highway tunnels have been increasing in China. As of the end of 2018, a total of 17,738 highway tunnels had been completed, covering over 17,240km. However, with increasing tunnels the number of tunnel accidents also rises. A tunnel provides a semi-closed, long space. In the event of a fire, the life of drivers and passengers will be threatened by abruptly increased ambient temperature, and concentration of smoke and other detrimental gases in the tunnel [1].

Currently, global scholars have done lots of research on temperature changes, ventilation and evacuation in the event of tunnel fires based on model test and numerical simulation and produced some results. Using Fluent, Wu and Bakar modeled highway tunnel fires in several rectangular tunnels and compared their characteristics through measurements of speed distribution in smoke flume area [2]. Xia Yongxu and Wang Yongdong conducted numerical simulation of ventilation in the highway tunnel in the event of a fire. Li Zhiqiang analyzed escape time under the combined effect of temperature and CO concentration using corrected Chladni formula and FED model as escape criteria. However, prior work mostly focuses on the development of tunnel fire and countermeasures with a lack of statistical analysis of tunnel fire characteristics [3].

In response, we collect 156 tunnel fire accidents at home and abroad and analyze their time and spatial distribution, causes and effects in this paper. We also propose appropriate measures and recommendations for fire accident prevention and escape to provide reference for improving safe operation of highway tunnels.



2. Distribution of Tunnel Fire Accidents

2.1. Time distribution of tunnel fire accidents

In order to study the pattern of tunnel fire accidents occurring throughout a year, the number of accidents in each month of a year is statistically analyzed as shown in Fig. 1:

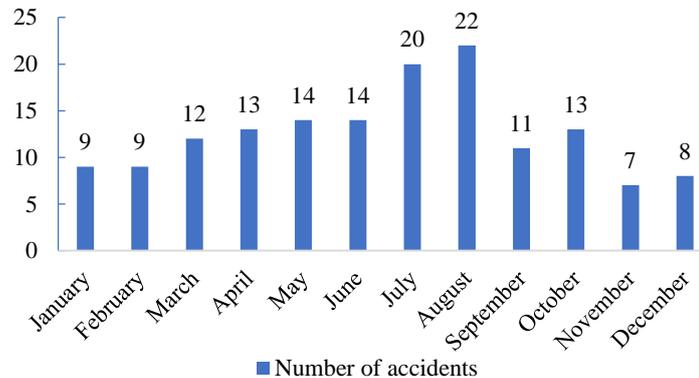


Fig 1. Distribution of tunnel fire accidents by month

As shown in Fig. 1, the overall pattern of the number of tunnel fire accidents is in parabolic distribution, with a gradual increase in the first half of the year, peaking at July and August (42 accidents in these two months making up 26.9%) before decreasing. The main reasons are an increase in road transport services after Spring Festival and in rainfall in spring and summer result in slippery road surface and thus more accidents. In the summer months of July and August, vehicles operating at high air temperatures are under more load and more prone to spontaneous combustion of tyre, engine and fuel tank. On the contrary, in the winter months of November to February the probability of truck and goods undergoing spontaneous combustion is low and the number of tunnel fire accidents in these four months is the lowest.

2.2. Spatial distribution of tunnel fire accidents

2.2.1. *Regional distribution characteristics.* The 104 tunnel fire accidents that occurred in China are statistically analyzed as shown in Fig. 2.

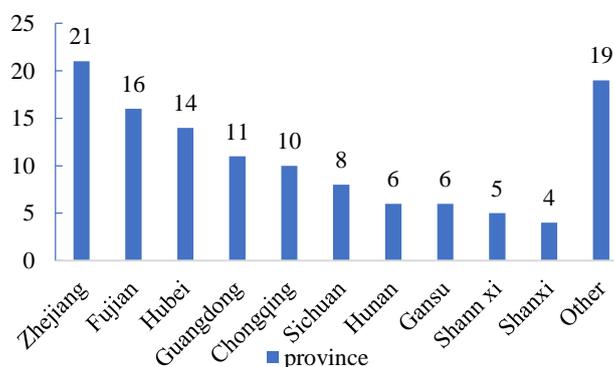


Fig 2. Distribution of tunnel fire accidents by province

The top ten provinces/municipality directly under the central government in terms of the number of accidents are concentrated in developed areas such as Zhejiang, Fujian and Guangdong or

mountainous areas such as Chongqing, Sichuan, Gansu and Shaanxi. The main reasons are as follows: in the former areas the numerous highway tunnels, complex transport and large numbers of goods vehicles increase the probability of tunnel fires whereas in the latter areas poor horizontal alignments of roads and large numbers of long steep slopes in mountains and on plateau are likely to cause traffic accidents.

2.2.2. Distribution inside the tunnel. With tunnel entrance and exit as reference point in the driving direction, the tunnel is divided into 3 zones: A (threshold zone, starting at tunnel portal and ends at 200m inside the tunnel from the portal); B (the interior zone); C (the exit zone, beginning at the point 200m from the exit and ends at the tunnel exit), as detailed in Fig. 3.

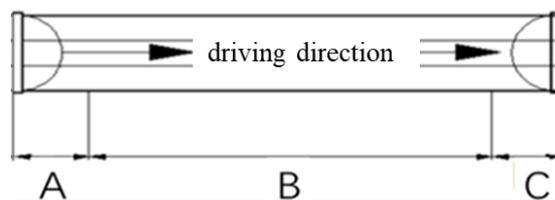


Fig 3. Zones for tunnel fire analysis

As shown in Fig. 4, 66 of the 105 tunnel fire accidents with known locations occurred near portals (Zones A and C), accounting for about 63%. This is because the drivers' vision is disturbed by the luminance difference between the interior and exterior of the tunnel, making them unable to avoid other vehicles inside the tunnel and result in rear-end and collisions; when vehicles catch fire the driver tends to drive the vehicle out of the tunnel or park it at the portal, thus increasing the fire frequency in Zones A and C.

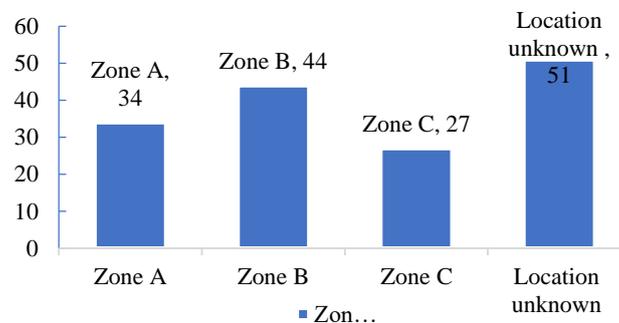


Fig 4. Statistics of number of accidents by location

2.2.3. Relationship with tunnel length. Tunnels are divided into four categories by length [4]: a. super long tunnel (over 3000m in length); b. long tunnel (1000m<L<3000m); c. medium long tunnel (500m <L<1000m); d. short tunnel (L≤500m). Statistical results are shown in Fig. 5.

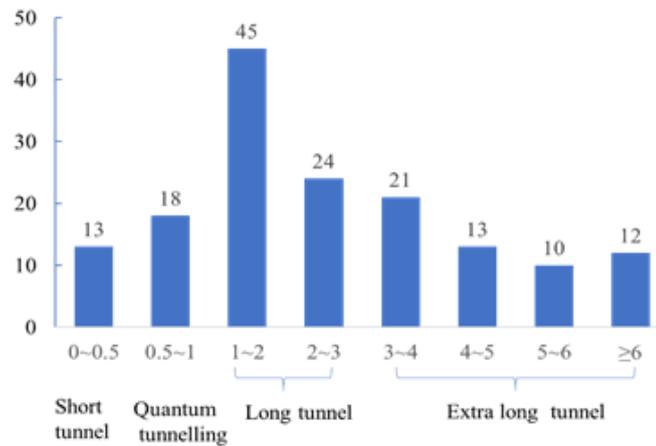


Fig 5. Relationship between tunnel length and the number of accidents

As shown in Fig. 5, the number of fire accidents rises with length, peaking at 1000m-2000m before falling. Specifically, 13 accidents or 8.3% occurred in short tunnels; 18 accidents or 11.6% occurred in medium long tunnels; 69 accidents or 44.2% occurred in long tunnels; 56 accidents or 35.9% occurred in super long tunnels.

Further analysis of casualties is performed as shown in Fig. 6: the number of casualties increases with increasing length, peaking at 1000m-4000m before falling.

This is because: 1) In the event of a fire in a short tunnel most drivers will drive the vehicle out of the tunnel in a short time whereas there is no enough time for them to drive the vehicle out of a tunnel which is long and super long; 2) when a vehicle catches fire in a long tunnel, it takes a longer time and is more difficult for the fire fighters to reach the scene, making the fire worse; 3) for a short tunnel the drivers do not need to adapt to sharp changes in environment whereas for a tunnel of 1000m-3000m in length, they experience "dark adaptation" and "bright adaptation" in a short time, resulting in more traffic accidents and more frequent fire accidents.

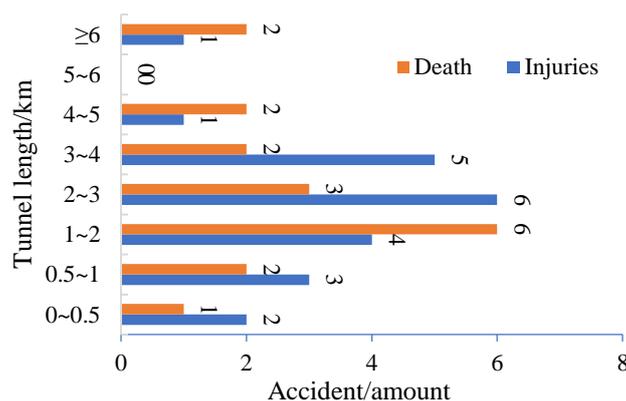


Fig 6. Relationship between the number of casualties and tunnel length

2.3. Distribution of fire accidents by model

In order to identify the models associated with the most frequent and the most serious tunnel fire accidents, main vehicle models corresponding to each accident are statistically analyzed, as shown in Fig. 7.

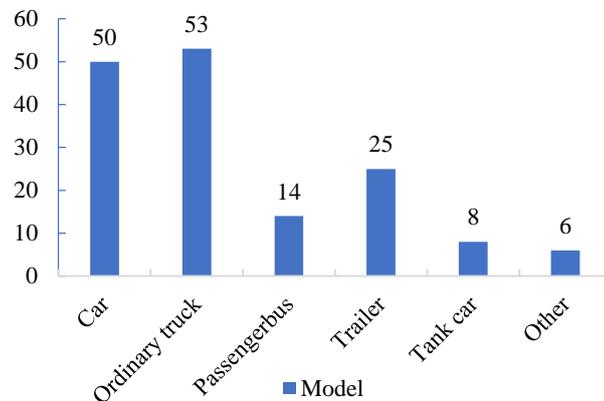


Fig 7. Distribution of tunnel fire accidents by vehicle model

As shown in Fig.7, main models in tunnel fire accidents are ordinary trucks and cars representing 32% and 34% respectively, followed by trailers, passenger buses and tank cars. Based on statistical analysis, truck and trailer fires are mostly caused by spontaneous combustion as a result of prolonged operation and overload; due to the large capacity of fuel tank and other possible flammable goods carried, the fire accidents are larger in scale and more serious when they occur. With a dense population in them, passenger buses are more likely to cause group casualties when fires occur. In addition, a total of 18 accidents involved various flammable, explosive or toxic goods which would cause secondary disaster and more severe casualties when they catch fire, explode or leak.

3. Analysis of Causes of Tunnel Fire Accidents

Given the complexity and dynamics of traffic in the tunnel, causes of tunnel fires vary. On the basis of case analysis the main causes of tunnel fires are divided into four groups: spontaneous combustion of vehicle, spontaneous combustion of goods, traffic accident and others (tunnel management, arson and so on), as shown in Fig. 8.

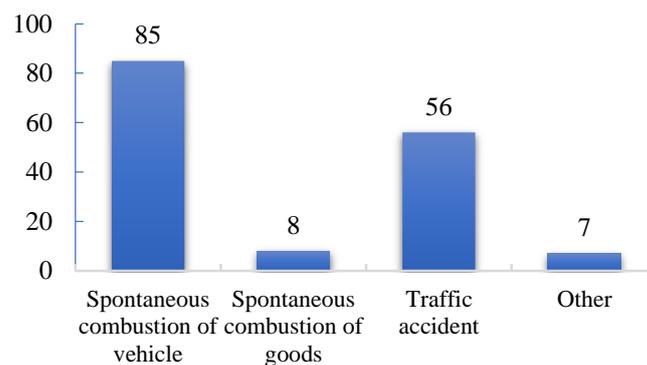


Fig 8. Causes of tunnel fire accidents

From Fig. 8 it can be seen that: the number of accidents attributed to spontaneous combustion of vehicle is 85 representing 54.5%; the number of fire accidents attributed to traffic accident is 56 representing 36%; the number of fire accidents attributed to spontaneous combustion of goods is 8 representing 5.1%; the number of fire accidents attributed to other causes is 7 representing 4.4%. Among these causes, spontaneous combustion of vehicle and traffic accident are the major causes of tunnel fire disaster.

Tunnel fire accidents caused by spontaneous combustion of vehicle and traffic accident are further analyzed statistically, as displayed in Fig. 9 and 10.

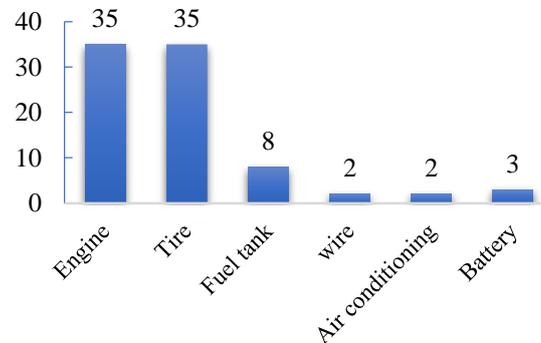


Fig 9. Classification of spontaneous combustion of vehicle and corresponding number of accidents

It can be seen that most spontaneous combustion of vehicle occurs at the engine and tire (35 accidents making up 41.2% respectively); other spontaneous combustion of vehicle occurs at the fuel tank and other locations (wire, battery and air conditioning), making up 17.6%. Most engine fires are caused by overheat due to prolonged operation of the vehicle and a few of them are caused by depletion of cooling water in the cooling water tank. Most tire fires are caused by over friction between the tire under heavy load and road surface, frequent application of brake on a long downgrade, and so on.

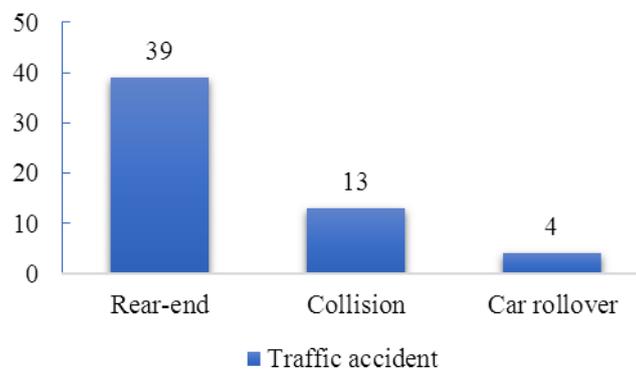


Fig 10. Distribution of forms of traffic accident

The most common form of traffic accident resulting in tunnel fires is rear-end (causing 39 fire accidents representing 69.6%) while collision and car rollover caused 14 tunnel fire accidents. This is because vehicles are not prone to collision or car rollover when operating at restricted speed in the tunnels most of which are one-way; on the contrary, vehicles in the tunnels are prone to rear-end when car-following distance is small and traveling speed dispersion is great.

4. Analyses of Tunnel Fire Consequences

Main consequences of tunnel fire accidents are casualties, vehicle damages, structural damages to the tunnel and traffic delay. These four consequences are analyzed and discussed respectively hereunder.

4.1. Casualties

The number of tunnel fire accidents leading to varying degrees of casualties is 24, of which 18 lead to 142 deaths (10.7%) and 22 lead to 287 injuries (12.9%). From calculation it is known that each

accident leads to 0.91 deaths and 1.84 injuries on average, compared to the average deaths/injuries (0.302/1.063) per accident from all traffic accidents in the period of 2013-2017 in China. This means the severity of tunnel fire accidents is far higher than the average level of traffic accidents. This is because temperatures inside the tunnel rise rapidly in the event of a fire and the smoke and detrimental gases generated during a fire event make it more difficult for motorists to escape, thus causing severe casualties. Table 1 lists some tunnel fire accidents that caused severe casualties.

Table 1. Example accidents causing severe casualties

Tunnel name	Date	Accident consequence
Gleinalm Tunnel	2001.8.6	5 deaths and 4 injuries
Huishan Tunnel	2010.7.4	24 deaths
Xueshan Tunnel	2012.5.8	2 deaths from burn and 31 injuries from choking
Yanhou Tunnel	2014.3.1	40 deaths and 12 injuries
Taojiakuang Tunnel	2017.5.9	12 deaths (including 11 children) and 1 serious injury
Maoliling Tunnel	2019.8.25	5 deaths and 36 injuries

4.2. Vehicle damage

Main combustible sources and inducements of all the tunnel fire accidents are related to vehicular activity inside the tunnel. Each of the 156 tunnel fire accidents caused damages to one or more vehicles. The cases show: when vehicles carrying hazardous chemicals and heavy trucks catch fire, the consequence is often more severe; under congested conditions inside the tunnel, secondary fire would occur, causing fire to adjacent vehicles. Table 2 lists the fire accident information and consequences for some of the tunnels under consideration.

Table 2. Selected tunnel fire accidents involving multiple vehicles

Tunnel name	Date	Number of vehicles	Consequence
Velsen Tunnel	1987.8.1	6	5 deaths, 5 injuries and burning up of all vehicles in the accident
Zhujiayan Tunnel	2010.10.23	10	2 deaths and damages to all vehicles in the accident
Futuyu 5# Tunnel	2011.4.8	9	15 deaths, 3 serious injuries and damages to all vehicles in the accident
New Qidaoliang Tunnel	2011.4.8	2	4 deaths, serious damages to the tunnel and damages to all vehicles in the accident
Feiluanling Tunnel	2014.5.1	3	Damages to all vehicles in the accident and over 100 people trapped in the tunnel

4.3. Damages to tunnel facilities and structure

Of the 156 accidents, 31 are ascertained to have caused to damages to tunnel structure and equipment. The heat release power of heavy vehicles in the tunnel is in the range of 30-100MW. In addition, the confinement nature of the tunnel allows the temperature of the tunnel crown near the ignition point to exceed 1000°C [4] in a very short time. At such temperature the adhesion of concrete and reinforcing steel bars in tunnel lining structure quickly drops causing loss of the capacity of tunnel structure; meanwhile, electricity, fans and other facilities inside the tunnel would be overloaded and even fail due to high temperatures, thus leading to economic loss. Table 3 lists some tunnel fire accidents involving serious damages to tunnels.

Table 3. Fire accidents leading to tunnel damages

Tunnel name	Date	Description of tunnel damages
Nihon-zaka Tunnel	1979.7.11	Spalling of tunnel roof in more than 1,000 square metres
Maoliling Tunnel	2002.1.10	Over 200m of lining burned up
Zhujiayan Tunnel	2010.10.23	Damage to tunnel lining
New Qidaoliang Tunnel	2011.4.8	Large amounts of concrete on sidewalls shattered by blast
Shibianzi Tunnel	2017.5.6	Serious damages to tunnel mechanical and electrical facilities
Jiangbeiling Tunnel	2018.11.23	Serious damages to power system, ventilation system, lighting fixtures, etc.

4.4. Traffic disruption

Traffic disruption has a serious impact on normal traffic flow and causes economic loss as indirect loss from tunnel fire accidents. Of the 156 tunnel fire accidents 32% caused less than 1h of traffic interruption; 15% caused 1-4h of traffic interruption; 28% caused 4-12h of traffic interruption; 25% caused over 12h of traffic interruption. These data suggest tunnel fire accidents have a huge impact on normal traffic operation. To avoid such losses, an optimum alternative route shall be selected in advance and in the event of a tunnel fire, road users shall be notified through communication means so as to reduce losses from traffic interruption.

Table 4. Selected tunnel fire accidents leading to traffic interruption

Tunnel name	Date	Duration of traffic interruption
Feiluanling Tunnel	2011.12.15	4h of traffic interruption
Xueshan Tunnel	2012.5.8	North and south lanes closed for nearly 6h
Mawu Tunnel	2017.8.20	Traffic on Nanchuan-Fuling Expressway interrupted for 1h
Donggengyao Tunnel	2017.9.13	Nearly 15h of traffic interruption
Maoliling Tunnel	2018.8.27	Road closed for 7 days
Jiangbeiling Tunnel	2018.11.23	Tunnel closed for emergency repair

5. Countermeasures

On the basis of the above statistical analyses of highway tunnel fire accidents in China, the following pertinent countermeasures and recommendations are proposed to prevent highway tunnel fire and mitigate its effect:

- To address spontaneous combustion of vehicles, the thermal imaging based vehicle spontaneous combustion warning system may be employed to monitor vehicle temperature distribution[5] through detection equipment and warn the driver of immediate spontaneous combustion so that the fire can be controlled in initial stage.
- Large trucks especially hazardous goods transport vehicles shall be subjected to stricter roadside check, for example by coding heavy trucks and their loads through GPS for real-time tracking and imposing serious penalties on offenders and overload; in addition, drivers of trucks and hazardous goods transport vehicles shall be periodically evaluated and trained including in vehicle operation safety, vehicle maintenance, emergency firefighting, etc[6].
- Summer is the season of frequent tunnel fire accidents. It is recommended to provide mobile inspection and prompt posts at watering stations to inspect each vehicle stopping at the station for water replenishment and communicate safety precautions.
- Fire accidents are concentrated in mountainous areas with dense tunnels. Such areas may be divided into zones and fire emergency response plans prepared for each area.

- To facilitate quick evacuation of tunnel occupants during an emergency, evacuation facilities need to be improved for example by providing continuous LED guidance strip and contour indicator lamps around the door to cross passages.

6. Conclusions

- Tunnel fire accidents are distributed in the shape of parabola throughout a year and concentrated in the summer months of July and August. Mountainous areas and developed areas see more accidents than other areas; accidents on steep slope and near tunnel entrance/exit are frequent. Tunnel fire accidents mostly involve cars and heavy trucks. The size of tunnel fire involving heavy trucks is often larger.

- Most tunnel fires are caused by spontaneous combustion of vehicle and traffic accidents. On average, each tunnel fire accident causes 0.91 deaths and 1.84 injuries, far higher than the average level of traffic accidents. Of the 156 tunnel fire accidents 31 caused serious damages to tunnel structure and 53% caused more than 4h of traffic interruption.

- To ensure safety operation of the tunnels, more work shall be done to educate drivers of heavy and hazardous goods vehicles on safety, to monitor high-temperature vehicles for early warning, to develop emergency response plans and put out potential fire in the initial stage.

- Current information on tunnel fire accidents remains scattered and multiple restrictions make it difficult to obtain comprehensive information and accurate data. To facilitate in-depth study into tunnel fire accidents, it is recommended that appropriate platforms and database be established for statistical analysis of such accidents.

Acknowledgements

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