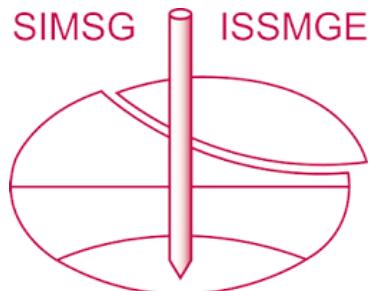


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Review on the Disaster Prevention and Rescue of High-speed Railway Long Tunnels

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ABSTRACT: The operation experiences of Japanese and European high-speed railway tunnels indicate that the train fire is the most dangerous disaster. The design and study on disaster prevention and rescue of the high-speed railway tunnels both aim at it. In this article, several topics are discussed. First, the train fire cases in railway tunnels are collected and the factors are analyzed. Second, present research works on the fireproofing of train, the fire scene in tunnel, the fireproofing of the tunnel lining, smoke control and the evacuation are generalized. The shortcomings of the domestic study are shown. In the end, possible research fields are discussed.

1 INTRODUCTION

In 2004, the State Council approved the Middle and Long Period Plan of the Railway Network. The Plan indicates that more than 12,000 kilometers of high-speed railway will be constructed in 20 years in China. The target speed of the passenger train is more than 200 kilometers per hour. The sixth raise of the railway speed on April 18th, 2007 indicates that China railway has stridden into the high-speed times. As the train runs so fast on high-speed railway and the minimum radius of railway curve is so big, more and more tunnels will be constructed when we select the high-speed railway route.

From the operation of the high-speed railway tunnel in Japan and European countries, we can learn that the train fire is the most dangerous disaster. So the disaster prevention design of the high-speed railway tunnel home and abroad is both focused on the train fire. This article also puts the train fire as the main question. In our country, there have been 7 serious train fires in railway tunnels. There are more than 180 deaths and the economic loss is more than 20 million Yuan. According to the incomplete statistic, there are more than 30 similar accidents abroad. The longer tunnel and the higher speed make the possibility of trouble in tunnel increase greatly.

In the coming 20 years, more than 892 kilometers of high-speed railway tunnel will be constructed in China, of which 8 tunnels are more than 10 kilometers in length. In our country, the high-speed railway tunnel has the characteristics of being large in amount, long, distributed widespread, complicated environmental and geological conditions and so on. The aim of this article is to review the present research works on the disaster prevention and rescue of high-speed railway tunnel and to discuss the future research.

2 ANALYSIS OF THE HIGH-SPEED RAILWAY TUNNEL FIRE

2.1 Train fire

Table 1. Train fires in tunnel home and abroad

Serial number	Name	Train pattern	The cause of the fire	Time	The number of the wounded(death)
1	No.46 tunnel on Fengsha line	wagon	Peccancy;track line trouble	1976.3	0
2	No.140 tunnel on Baocheng line	wagon	Trigging suddenly;oilcan crack	1976.10	23(75)

3	Shilishan No.2 tunnel on Longhai line	wagon	manhole uncovered; rail rupture	1987.8	(2)
4	Liziyuan tunnel on Xiangyu line	wagon	contact net discharge	1990.7	14(4)
5	Dayaoshan tunnel on Jingguang line	wagon	smoke	1991.7	20(12)
6	No.18 tunnel on Qingzang line	wagon	manhole uncovered;track line trouble	1992.9	0
7	Linjiachuan Tunnel on Xiyan line	wagon	Oil outside; Trigging suddenly	1993.6	10(8)
8	Japan Shengjushan tunnel	carriage	Rheostat overreach	1947.4	73 (28)
9	Japan No.18 tunnel on Togoshi line	carriage	Breaker trouble; Rheostat overreach	1956.3	42 (1)
10	Japan Hokuriku tunnel	carriage	wiring creepage;dining car on fire	1972.11	715 (30)
11	Japan Acoma tunnel	carriage	high voltage string rupture	1987.9	48 (1)
12	Channel tunnel	wagon	carriage on fire	1996.11	0
13	England Summit tunnel	wagon	Oil mass; striking on fire	1984.12	0
14	American Heldson tunnel	carriage	Rheostat trouble	1969.5	8 (1)
15	American Kansas tunnel	wagon	digression	1974.6	unknown
16	American San Francisco tunnel	carriage	Short circuit	1979.1	17 (1)
17	American BART tunnel	carriage	Short circuit	1979.1	56(1)
18	French Coronus tunnel	wagon	collision	1971.3	(2)

In the recent years, the train fires that happened in railway tunnels home and abroad are shown in Table 1. According to the table ,we can see that in the 7 domestic train fires, only 1 of them is carriage fire, and the rest are all freight train fires. According to the 11 train fires abroad,7 of them are all carriage fires and the fires are mainly caused by the wiring troubles.4 of them are wagons. Some are caused by digression and strike. In general, the causes of the fire are complicated and the factors are associated.

2.2 Analysis

The causes of the train fire in high-speed railway tunnel can be divided into four sides:

- Artificial factors. They may include the peccancy of the chauffeur's operation, tinder and hazards taken by the passengers, smoking, arson and so on.
- Train's factors such as electric trouble, air-conditioning trouble and so on.
- Environmental factors such as the track line's badness or small curve radius.
- Other factors such as communication troubles or collision induced by signal faults.

3 REVIEW ON HIGH-SPEED RAILWAY TUNNEL FIRE

The disaster prevention and rescue of the high-speed railway tunnel include “disaster prevention” and “rescue”. “Disaster prevention” means avoidance of fire and controlling the development of the fire. “Rescue ” has two meanings. One is to insure the people’s evacuation under the fire. The other is fire fighting and rehabilitation. The “rescue ” in this article points to the evacuation.

The following text is to discuss the present research works on the fireproofing of the train, fire scene in tunnel, the fireproofing of the lining, smoke control and the evacuation.

3.1 The fireproofing of the train

The combustibles in high-speed railway tunnel include the train bodywork, baggage, the fixed establishment and so on. The burning combustibles gave birth to poisonous gas or smoke. The bad ventilation pricks up the ill burning. The poisonous gas and smoke not only hurt the passenger but also make the evacuation difficult.

The fireproofing requirements of the high-speed train must be higher than common train. Shinkansen(Japan) adopted silver-contained lead to improve the fire proofing of the contact lead. The establishments in the train such as the crust, liner, floor, seat and the curtain all adopt fireproof materials. Germany has developed new fireproofing train which keeps to the DIN5510 standard. The unqualified trains will be rejected. TGV(France) set the fireproofing standard for the different parts of the train. American BARTC high-speed train have a rigid regulation for the materials of the different parts, such as the burning velocity, the smoke density after 4 minutes' complete burning of the materials.

Some countries try to control the initial structure's distortion to insure the evacuation of the passengers. TGV checks the train's intensity and rigidity under 350°C with 15 minutes' burning. ICE(Germany) ensures that the trains can continue moving under the 15 minutes' complete burning.

China has established some standards on the fireproofing of the train, such as GB/T 12817, TB/T 2402-93, TB/T 2640-1995, TB/T 2702-1996. However, they are all aimed at the common trains.

3.2 The fire scene in tunnel

The fire scene in tunnel is the description of the fire development. It is critical to research the fire. The key to the fire scene is to make sure the heat release rate(HRR) movement with the time.

The fire scene in tunnel is usually described by t^2 model, as formula (1) shows. It means that at the beginning of the fire HRR has direct ratio to t^2 . However, after the time t_0 , HRR levels off to a certain value.

$$Q = \begin{cases} at^2 & (t \leq t_0) \\ Q_{\max} & (t > t_0) \end{cases} \quad (1)$$

Q —HRR(MW);

a —the development velocity of the fire(MW/s²);

t —time(s); t_0 is the critical time.

Nine European nations cooperated in the EUREKA project EU 499 FIRETUN. Their common efforts formed the basis for a remarkable condensed instrumentation of a 2300-m-long test tunnel. The most important results of the project are the tunnel fire's maximum temperatures and maximum HRR (Heat Release Rate), as the Table.2 shows.

Table 2 Heat release rate of different vehicles

Type of the vehicle	Passenger car	Bus/lorry	Heavy goods vehicle	Railway coaches
Max. HRR (MW)	3~5	15~20	50~100	15~20
Max. temperature (°C)	400~500	700~800	1000~1200	800~900

However, as HRR is related to the composition of the combustible, the content of the oxygen, the geometry of a tunnel, ventilation and so on, it is difficult to ensure the HRR.

Helseden(1976) estimated the HRR of the heavy goods vehicle(HGV) fire is 20 MW. After that many researchers adopted this value. However, the HRR measured in the real tunnels was more than 100 MW. Malhotra(1993) pointed out the HRR of the HGV fire under the longitudinal ventilation reached 100 MW. Carvel(2001) founded that the longitudinal ventilation had a great impact on the HRR of a HGV fire. A 3m/s airflow velocity may cause the fire size to 5 times in its grown phase; A 10m/s airflow velocity may cause the fire size to 10 times in its grown phase. A 1.5m/s airflow velocity will not significantly affect the fire size or rate of development of a cars fire.

Chow (1996) showed that the HRR of the metro fire will be up to 35MW after 10 minutes' burning. Feng (2002) considered that the maximum HRR will be 13.6MW. Gu(2005) thought that the HRR of the old-type trains will be 15MW but the HRR of the new ones will be only 7.5MW because the new ones adopted nonflammable materials. Yang(2006) advised that the HRR of the underground train should be 10MW and the HRR of the moved combustible should be 5MW.

3.3 The fireproofing of the lining

The fire in tunnel has the characteristic of extending rapidly, producing amount of smoke and high temperature. The temperature of the flame center is usually up to 1000°C. The intensity of the lining decreases and sometimes it may developed into spalling or even collapse. At the same time, It may cost large amount of manpowers and resources. Especially if it is a tunnel under a river or a sea, the result may be more severe.

The usual fireproofing measures are as following:

- The concrete of the lining can be added some fibers;
- The lining adopted heat-insulated concrete.
- The face of the lining can be rendered heat-insulated dope.
- Fireproofing board.
- The lining can be sprayed by reinforced grout.

The foreign research is concentrated on the topics such as the development of the fireproof concrete, the spalling and the stability of the lining under the fire.

Ibrahim A. El-Arabi(1992) made a research on the distortion and stress of the lining under the fire. His research considered two factors, one is the action between the structure and the earth and the other is the rigidity loss due to the high temperature. H.-W. Dorgarten(2004) developed a fire resistant structural concrete ‘System HOCHTIEF’ using synthetic fibers and special aggregates. Furitsu Yasuda(2004) made a research on three different fire protection measure applied in the lining: board type, silica fiber blanket type and spray mortar type. They concluded: (1) Spalling of concrete occurs and it reaches up to 60 mm if there is no fire protection on the surface.(2) Compressive strength of the concrete drops to one half of the unheated value and Young’s modulus to one quarter by the heating.(3) All the selected fire protections of the board type, silica fiber blanket type and spray mortar type keep the temperature of the segment less than 260 °C. The temperature of the joint metal is kept lower than 100 °C and the sealing for water tightness is protected unharmed.

K. Savov(2005) made a research on the stability of shallow tunnels subjected to fire load. The article considered that after the fire the lining of the shallow tunnel cannot maintain the additive load because of the thermal degradation. Based on different fire-load scenarios and spalling histories, the article made a mechanic analysis on the lining and try to answer to the central question “whether or not spalling can cause collapse of shallow tunnels”. A Beard(2005) discussed the fireproofing measures of the lining and the mechanic nature of the lining. A.G. Smith(2007) assessed how exposed sandstone is likely to respond in a tunnel fire by means of laboratory and field tests.,

The domestic research on the field started in the 1990s. In 1994, Southwest Research Institute of CREC make a research on “the assessment of the lining’s damage and the rehabilitation”. Then the achievements on the lining’s damage model under the fire reached international advanced level . Zhu (2006) studied mechanical property of C50 concrete, CF50 steel fiber concrete and PC50 PP fiber concrete after different high temperature effects were completed.

3.4 Smoke control

The former tunnel fires indicate that the smoke and poisonous gas is fatal to the passenger. Moreover the key to smoke control is to control the “critical velocity”. The critical velocity is related to many factors such as Hurth geometry of the tunnel, gradient, the friction of the wall, ventilation. The research on the smoke control is concentrated on the calculation of the critical velocity.

Thomas(1968) firstly advanced calculating the critical velocity based on the Froude number. Heselden(1976) presented the calculation formula and the formula is popularly applied.

Yasushi Oka(1995) made a test in a model tunnel and the results indicated that the critical velocity is proportional to $Q^{1/3}$ for small Q, but the critical velocity is independent of Q for large Q. G. T. Atkinson(1996) made a test in the same model tunnel to know how gradient influences the smoke movement. J.P. Kunsch(1998) considered that the critical velocity is independent of Q when Q is more than 2MW.

The previous research is based on one-dimension assumption. Y. Wu (2000) made a model test and numerical simulation to research 5 different tunnel sections that have the same height but different width.

The study used dimensionless velocity and dimensionless heat release rate with the tunnel hydraulic height (tunnel mean hydraulic diameter) as the characteristic length in the data analysis. The article gave the improved formula.

Jae(2007) considered that ventilation would influence the HRR. The study advised that the calculation of the critical velocity should be based on the varied HRR by ventilation velocity.

The domestic study on the smoke control started late. The domestic researchers all analyzed the factors influencing on the critical velocity by numerical simulation.

Zhao(2005) considered that the critical velocity is independent of Q when Q is more than 30MW. Zhang(2005) simulated the critical velocity under the different gradient and gave the gradient-modified formula to calculate the critical velocity. Zhou(2006) simulated how different shield tunnel sections (one-lane round, one-stride rectangle and two-strides rectangle) influenced the critical velocity. The results indicated that the critical velocity of one-lane round tunnel was the most but the velocity of two-stride rectangle tunnel is the least. Xu(2007) concluded that the critical velocity was proportional to Q when Q was smaller than 30MW but independent of Q when Q was between 40MW and 80MW.

3.5 Evacuation

According to the fire fighting practice in tunnel fire home and abroad, the differences on the evacuation among the road tunnel, metro, railway tunnel are as Table 3 shows.

Table 3 The evacuation methods of the railway tunnel, road tunnel and subway

	Road tunnel	Railway tunnel	Metro
Location	City or mountainous area	City or mountainous area	City
Evacuation type	Service tunnel、under the roadway、cross passage、parallel drift、shaft	running out、emergency station、Service tunnel、cross passage parallel drift、shaft	station、cross passage
Evacuation passage	wide	narrow	Very narrow
Arriving time of the fire engine controlling of the vehicle	5~10min	10~60min	5~10min
Arriving type of the fire engine	Individual control	Auto control	Auto control
	tunnel opening, auto car	tunnel opening, train	stop, train

As the table shows, the evacuation of the railways(high-speed railway included) can be divided into three types: longitudinal evacuation, cross evacuation and mixed evacuation.

— longitudinal evacuation. It means that the train on fire can be draught out of the tunnel if the power is valid. In 1973 Japan made a passenger train's fire test. The result indicated that it was safe for the train to continue running for 15min after being on fire. In Europe there is a similar regulation: the train on fire can continue running 20 kilometers.

— cross evacuation. The exits includes service tunnel, cross passage, parallel drift, shaft and so on.

— mixed evacuation. It means that the train on fire can run to the emergency station in the middle of the tunnel and then people can evacuate through the cross passage. The power of the train should be valid. The space between two emergency stations is about 20 kilometers such as Japanese Seikan Tunnel, Swiss New Gotthard Base Tunnel and Loetschberg Base Tunnel.

In the longitudinal evacuation, we must ensure that the people in the carriage on fire should evacuate to the other carriages. In the cross evacuation, we must ensure that the available time of evacuation should be smaller than the requisite time of evacuation.

The study home and abroad is concentrated on the cross evacuation. The researchers assessed the safety of the tunnel and discussed the setting of the evacuation passage through the numerical simulation.

— According to whether the smoke's thickness, temperature and visibility under the fire are up to alarm value or not, the available time can be obtained by simulation using the software such as FDS,

FLUENT、POENICS.

—The requisite time of evacuation includes alarming time, responding time and evacuation time. The evacuation time is related to evacuation route, the passenger's number, mind, ability, age and so on. There are many good evacuation models such as American EVACNET4、EXIT89 and Japanese EVACS. The domestic research just started. Yu(2006) advanced a model named Tunev special for the tunnel.

4 DISCUSSION OF THE FUTURE STUDY

The disaster prevention and rescue of high-speed railway tunnel is a systemic engineering. To make the tunnel on a high level of safety, we should make a reasonable setting of alarm system, fire fighting system, smoke controlling system, train's fireproofing, tunnel structure's fire proofing and the evacuation passage and so on. The correlative standards are imperative.

—The possibility of the high-speed train fire is bigger because of the high speed. So the standards of the common train are on the low side for the high-speed train. Our country should establish the suitable standards making reference to the overseas standards.

—There is not a consistent formula of the HRR home and abroad. And that the nonflammable materials adopted in the high-speed train should influence the HRR.

—The section of the high-speed railway tunnel is usually bigger and the lining is thicker. So the fireproofing of the lining needs special research. Different lining type such as monolayer lining, composite lining and the segment should be studied. The problems such as fireproofing method, the mechanic performance under the fire, the damage detection and the assessment of the bearing capacity should be on research.

—The domestic study on the smoke control started late. There are few model tests and locale trials. Also the theory is needed. It is necessary to make a research on how HRR, the geometry, gradient, ventilation influence the critical velocity.

—The evacuation model is the key to the evacuation research. In the longitudinal evacuation, we must be sure that the people in the carriage on fire should evacuate to the other carriages even if the train wind will influence the fire. In the cross evacuation, we must set the reasonable evacuation passage to make the available time of evacuation smaller than the required time of evacuation.

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