Research on Risk Assessment Technology for Fire Accidents in long Tunnels of Mountainous Expressways

Weili Wang[1], Yongguo Zuo[1], Xiaoming Zhong[2] and Guopan Liu[1,*]

[1]Guizhou Transportation Planning Survey & Design Academe Company Limited, Guiyang, Guizhou, 550000, China
[2] CHELBI Engineering Consultants, Inc., Beijing, Beijing, 100000, China

*Corresponding author's e-mail: 752219556@qq.com

Abstract. Mountainous expressway tunnels have tiny spaces, making population evacuation difficult if a fire breaks out. Therefore, the safety risk of tunnel fire accidents must be addressed. In this paper, we comprehensively sort out the fire accident risk sources in long tunnels of mountainous expressways, establish a fire accident risk assessment model based on risk factors and guarantee factors, and calculate the fire accident risk assessment value of a long tunnel in Guizhou Province as an example. The results show that the fire accident risk assessment values in the upward and downward direction are 90.74 and 89.06, and the fire accident risk levels in the upward and downward direction are class I and class II. The risk coefficient in the downward direction is higher than that in the upward direction. The research results can improve the risk control ability of fire accidents in expressway tunnels and strengthen the risk control of expressway tunnel safety.

Keywords: mountainous expressways; long tunnels; risk factors; guarantee factors

1 Introduction

Guizhou Province is located in the Yunnan-Guizhou Plateau, 92.5% of the province is mountainous or hilly. Expressways in Guizhou province are mainly mountainous expressways with a large number of long tunnels. According to statistics, by the end of 2022, the province's total length of expressway tunnels amounted to 2,840,483 linear meters, with long tunnels amounting to 1,511,511 linear meters The tunnel, with its confined space and harsh environment, serves as the key control point for the overall transportation safety system. Traffic accidents inside tunnels can easily lead to fire accidents, and the tight construction inside tunnels hinders the dissipation of fire smoke and heat, which is not conducive to the entry of rescue forces, and brings great risks to the evacuation and rescue of people in tunnels. In the case of fires, it can easily lead to mass fatalities and injuries, resulting in a terrible social impact. Therefore, the safety risk of tunnel fire accidents must be paid great attention to.

At present, research on fire assessment of long tunnels on expressways in China mainly focuses on the field of ventilation and smoke exhaust during operation [1].

G. Zhao et al. (eds.), *Proceedings of the 2024 7th International Symposium on Traffic Transportation and Civil Architecture (ISTTCA 2024)*, Advances in Engineering Research 241,
https://doi.org/10.2991/978-94-6463-514-0_26

There is no systematic research on fire accident risk assessment of long tunnels on expressways in mountainous areas in China [2-3]. Currently, the risk management for fire accidents in long tunnels on expressways mainly focuses on the operation, maintenance, and regular maintenance of existing fire-fighting facilities, without systematically conducting fire accident risk assessments.

The risk assessment model of tunnel fire accidents in the long tunnel of the mountainous expressway is established by using risk factors and guarantee factors. Taking a long tunnel in Guizhou Province as an example, the accident risk index of tunnel fires is quantitatively calculated, and the corresponding technical standards are used to evaluate the risk status of tunnel fires. Tunnel operation and management units can adopt corresponding graded control measures based on the risk assessment level of fire accidents in long tunnels of mountainous expressways, timely discover technical omissions and safety hazards in tunnels within their jurisdiction, and take correct safety measures to minimize the occurrence of fire accidents. This is of great significance in reducing tunnel fire risks, enhancing tunnel traffic capacity, and avoiding major casualties and property losses.

2 Risk Assessment Method for Fire Accidents in long Tunnels of Mountainous Expressways

After a comprehensive study of the risk sources of fire accidents in long tunnels of mountainous expressways, establish the risk factor assessment model of fire accidents in long tunnels of mountain expressways and the protection factor assessment model of fire accidents in long tunnels of mountain expressways, adopt the risk factor values to evaluate the risk level of fire accidents in tunnels, adopt the guarantee factor values to assess the level of protection of personal property safety in the case of fire accidents in tunnels. Finally, the risk factors and the guarantee factors are considered together to evaluate the risk level of fire accidents in long tunnels of mountain expressways.

Specific analytical steps for its assessment methodology:

(1) Determine the categories of risk factors for fire accidents in long tunnels of mountain expressways, evaluate and calculate the risk factor values;

(2) Determine the category of guarantee factors for fire accidents in long tunnels of mountain expressways, evaluate and calculate the guarantee factor values;

(3) Assessment of the fire risk level of the tunnel based on the results of the calculations.

Development of a model for assessing the risk of fire accidents in long tunnels on mountain expressways:

$$D = \frac{B}{F} \tag{1}$$

In equation (1): where D is the risk assessment value, B is the guarantee factor value, and F is the risk factor value. The risk grading criteria for fire accidents in long tunnels of mountain expressways are shown in Table 1.

Table 1. Risk classification criteria.

Risk level	Risk assessment value
Class I (Low risk)	≥90
Class II (General risk)	[80,90)
Class III (High risk)	[70,80)
Class IV (Significant risk)	[0,70)

3 A Model for the Risk Factors of Fire Accidents in long Tunnels of Mountainous Expressways

3.1 Formula for Calculating the Risk Factor Values

In the model to quantify the risk factor values, based on the previous research results, the most critical point is the risk factors. Summarize all the factors that may lead to fire accidents in tunnels, score the various types of risk factors, and convert the risk parameters to derive the risk factor. According to the actual situation of road tunnel operation safety in China, combined with the results of the provincial questionnaire survey, and drawing on the relevant results of the Euro TAP (European Tunnel Assessment Program), a comprehensive formulation of the conversion formula for the risk factor F is shown in equation (2):

$$F = \begin{cases} \frac{2}{375} \times \sum_{i=1}^{n} \gamma_i F_i + 0.6 & \sum_{i=1}^{n} \gamma_i F_i \leq 75 \\ 1 & \sum_{i=1}^{n} \gamma_i F_i > 75 \end{cases} \tag{2}$$

In equation (2): where γ_i is the weight of sub-risk factors, %. F_i is the value of sub-risk factor score.

3.2 Risk Factor Categories

Following the compilation of fire accident risk factors in expressway tunnels as suggested by earlier researchers, the scoring value of these risk factors primarily depends on the tunnel's vehicle kilometers, lane traffic volume, large vehicle kilometers, the transit of hazardous goods carriers, tunnel alignment, civil engineering frameworks, and other seven risk factors [4-5]. Currently, integrating hands-on engineering expertise, the significance of each sub-linear element and the evaluation scores are ascertained as depicted in Table 2.

Table 2. Indicators for the assessment of sub-risk factors.

Sub-risk factors (Score)		f_i
Annual million kilometers $F_1=f_1$ γ_1=15%	0~2 (17)	f_1
	2~5 (25)	
	5~10 (32)	
	10~15 (37)	
	15~20 (46)	
	20~30 (52)	
	30~40 (60)	
	40~50 (74)	
	50~70 (81)	
	≥ 70 (100)	
Lane traffic volume $F_2=f_2$ γ_2=15%	0~2 (17)	f_2
	2~5 (25)	
	5~10 (32)	
	10~15 (37)	
	15~20 (46)	
	20~30 (52)	
	30~40 (60)	
	40~50 (74)	
	50~70 (81)	
	≥ 70 (100)	
Annual million kilometers of large cars $F_3=f_3$ γ_3=19%	0~1 (12)	f_3
	1~2 (15)	
	2~5 (19)	
	5~10 (28)	
	10~15 (36)	
	15~20 (43)	
	20~25 (51)	
	25~30 (68)	
	30~35 (74)	
	≥ 35 (100)	
Dangerous goods $F_4=f_4$ γ_4=23%	Prohibition (11)	f_4
	Controlled (56)	
	Free (100)	
Tunnel linearity $F_5=f_5+f_6+f_7$ γ_5=12%	Distance between mainline entrances and tunnels less than minimum clearances (13)	f_5
	The interweaving of traffic flow in the tunnel (15)	f_6
	The longitudinal slope is greater than 3%, the radius of the horizontal curve is more than the average value (42)	f_7
	Located on a long steep downhill straight section (45)	

	The longitudinal slope is greater than 3%, the radius of the horizontal curve is less than the average value (53)	
	Located on the long steep downhill section, the radius of the horizontal curve is more than the average value (61)	
	Located on the long steep downhill section, the radius of the horizontal curve is less than the average value (72)	
Civil engineering $F_6=f_8+f_9+\ldots+f_{19}$ $\gamma_6=8\%$	Cave (category 0,1,2) (3)	f_8
	Cave (category 3) (13)	
	Portal (category 0,1,2) (1)	f_9
	Portal (category 3) (6)	
	Lining (category 0,1,2) (4)	f_{10}
	Lining (category 3) (27)	
	Asphalt road surface (0)	f_{11}
	Concrete road surface (4)	
	PCI $\geq$ 90 (0)	f_{12}
	PCI $\in$ (80,90] (0.5)	
	PCI $\in$ (70,80] (1)	
	PCI $\in$ (60,70] (1.5)	
	PCI $\leq$ 60 (2)	
	PBI $\geq$ 90 (0)	f_{13}
	PBI $\in$ (80,90] (0.5)	
	PBI $\in$ (70,80] (1)	
	PBI $\in$ (60,70] (1.5)	
	PBI $\leq$ 60 (2)	
	SRI $\geq$ 90 (0)	f_{14}
	SRI $\in$ (80,90] (0.5)	
	SRI $\in$ (70,80] (1)	
	SRI $\in$ (60,70] (1.5)	
	SRI $\leq$ 60 (2)	
	Service road (category 0,1,2) (3)	f_{15}
	Service road (category 3) (5)	
	Drainage facility (category 0,1,2) (3)	f_{16}
	Drainage facility (category 3) (8)	
	Suspended ceiling (category 0,1,2) (4)	f_{17}
	Suspended ceiling (category 3) (11)	
	Interior decoration (category 0,1,2) (3)	f_{18}
	Interior decoration (category 0,1,2) (5)	
	Graticule (category 0,1,2) (3)	f_{19}
	Graticule (category 3) (9)	
Other risks $F_7=f_{20}+f_{21}+f_{22}$ $\gamma_7=8\%$	Always congested (46)	f_{20}
	Morning and evening peak congestion (28)	

Sometimes congested (20)	
Rare congested (7)	
Group of tunnels (19)	f_{21}
Two or more fire incidents in the past year (35)	f_{22}

4 A Model for the Guarantee Factors of Fire Accidents in Long Tunnels of Mountainous Expressways

4.1 Formula for Calculating the Guarantee Factor Values

The conversion formula for the guarantee factor is：

$$B = \sum_{j=1}^{n} \lambda_j B_j \tag{3}$$

In equation (3): where λ_j is the weight of the sub- guarantee factors, %. B_j is the value of the sub-guarantee factor scores.

The installation and maintenance of firefighting and emergency response systems in lengthy tunnels on expressways has an impact on whether the extent and severity of fire incidents can be controlled in a timely and effective manner when they occur. As a result, long tunnel guarantee elements are primarily based on the installation and maintenance of firefighting and emergency response systems in (particularly) long tunnels.

At present, the standards for setting up firefighting and emergency response systems in expressway tunnels are mainly determined according to the "Specifications for Design of Expressway Tunnels Section 2 Traffic Engineering and Affiliated Facilities" (JTG D70/2-2014), which divides the tunnel level (A+, A, B, C, and D) by integrally weighing the length of a single tunnel and the average daily traffic volume of a single tunnel predicted for the design year, then determines the types of firefighting facilities that should be set up in the tunnel. The firefighting and emergency response systems installed in some tunnels that have been in operation for a long time do not meet the actual operating conditions and cannot satisfy the requirements for fire safety in tunnels. Therefore, it is possible to judge the need for electromechanical upgrading by the results of the assessment of the risk of fire accidents in long tunnels on expressways.

The "Technical Specifications of Maintenance for Expressway Tunnel" (JTG H12-2015) serves as the primary framework for managing and maintaining the expressway tunnel's firefighting and emergency system. The technical condition assessment of electromechanical facilities should be based on the information of daily inspection, regular maintenance, and periodic maintenance, combined with the statistics of equipment intact rate, to determine the electromechanical condition level of electromechanical facilities. Mechanical and electrical facilities of each sub-category of technical condition assessment value are divided into 0, 1, 2, and 3, the lowest is 3, condition assessment value of 3: power supply and distribution facilities and equipment intact <85%; lighting facilities and equipment intact <74%; ventilation facilities and equipment intact <82%; fire facilities and equipment intact <89%; monitoring and communication facilities and equipment intact <81%. When evaluating the condition value of 3, special projects should be implemented, daily inspection should be strengthened and traffic control measures should be taken. Therefore, when assessing the fire safety assessment of expressway tunnels, when assessing the safeguard factors of a sub-item of electromechanical facilities in the technical status of the current "Technical Specifications of Maintenance for Expressway Tunnel" (JTG H12) rated as 3, the index score value should be zero points.

4.2 Guarantee Factor Categories

Based on a detailed study of relevant national standards, the guarantee factor scoring value is mainly considered from the tunnel ventilation facilities, lighting facilities, power supply facilities, traffic monitoring facilities, environmental monitoring facilities, traffic control facilities, escape and rescue facilities, firefighting facilities, communication facilities, and emergency management, as shown in Table 3 [6].

Table 3. Indicators for the assessment of sub-guarantee factors.

	Sub-guarantee factors[a,b] (Score)	b_i
	Ventilation environment testing facilities (9)	b_1
	Ventilation capacity (11)	b_2
	Technical program for ventilation operation (14)	b_3
Ventilation facilities	Fan Performance (18)	b_4
$B_1=b_1+b_2+...+b_9$	Fan performance testing system (6)	b_5
γ_1=10%	Frequency-controlled ventilation systems (7)	b_6
	Fire evacuation drill (10)	b_7
	Fire smoke evacuation strategy (12)	b_8
	Vertical wind speed control (13)	b_9
	Emergency lighting (32)	b_{10}
Lighting facilities	Pedestrian crosswalk lighting (10)	b_{11}
$B_2=b_{10}+b_{11}+...+b_{14}$	Vehicular crosswalk lighting (10)	b_{12}
γ_2=9%	Cave approach lighting (23)	b_{13}
	Active guidance beacon (25)	b_{14}
	Power monitoring equipment (10)	b_{15}
	Low-voltage distribution systems (11)	b_{16}
Power supply facilities	Emergency power supply (13)	b_{17}
	Uninterruptible power supply units (13)	b_{18}
$B_3=b_{15}+b_{16}+...+b_{24}$	Electricity monitoring facilities (6)	b_{19}
γ_3=10%	Electrical relay protection (8)	b_{20}
	Own power generation equipment (8)	b_{21}
	Dual power supply automatic input device (9)	b_{22}

	Distribution line end switching for fire-fighting electrical equipment (9)	b_{23}
	Electrical fire monitoring systems (13)	b_{24}
Traffic monitoring facilities $B_4=b_{25}+b_{26}+\ldots+b_{32}$ γ_4=10%	Tunnel camera (19)	b_{25}
	Video event detection (21)	b_{26}
	Bayonet speed measuring (8)	b_{27}
	Large screen projection (9)	b_{28}
	Closed-circuit television monitoring (10)	b_{29}
	Congestion detection (10)	b_{30}
	Cross-channel monitoring (11)	b_{31}
	Manned (12)	b_{32}
Environmental monitoring facilities $B_5=b_{33}+b_{34}+\ldots+b_{37}$ γ_5=7%	NO_2 Detectors (15)	b_{33}
	CO Detectors (19)	b_{34}
	Wind speed and direction detectors (19)	b_{35}
	Luminance detectors (21)	b_{36}
	Visibility detectors (26)	b_{37}
Traffic control facilities $B_6=b_{38}+b_{39}+\ldots+b_{43}$ γ_6=9%	Traffic lights (18)	b_{38}
	Lane indicators (19)	b_{39}
	Graticule (19)	b_{40}
	Variable message signs (21)	b_{41}
	Variable speed limit signs (11)	b_{42}
	Physical measures to close the tunnel (12)	b_{43}
Escape facilities $B_7=b_{44}+b_{45}+\ldots+b_{53}$ γ_7=11%	Emergency parking zone (13)	b_{44}
	With pedestrian crossings (9)	b_{45}
	Spacing of pedestrian crossings >350m (5) Spacing of pedestrian crossings =350m (13) Spacing of pedestrian crossings =250m (19)	b_{46}
	With vehicular crossings (10)	b_{47}
	Spacing of vehicular crossings >1000m (7) Spacing of vehicular crossings =1000m (11) Spacing of vehicular crossings =750m (15)	b_{48}
	Liaison channel (6)	b_{49}
	Evacuation sign (8)	b_{50}
	Cross-channel signs (8)	b_{51}
	Cross-channel signage (prominent) (6)	b_{52}
	Evacuation sign (optimal) (6)	b_{53}
Firefighting facilities $B_8=b_{54}+b_{55}+\ldots+b_{71}$ γ_8=14%	Fire alarm controller (6)	b_{54}
	Manual alarm controller (8)	b_{55}
	Fire detectors (8)	b_{56}
	Fixed fire extinguishers (4)	b_{57}
	Fire hydrant (6)	b_{58}
	Fire-fighting pool (6)	b_{59}
	Signs for fire protection facilities (6)	b_{60}
	Fire extinguishers (12)	b_{61}
	Gas extinguishing system (4)	b_{62}

	Fire pump inspection system (4)	b_{63}
	Fire-fighting pool monitoring facility (4)	b_{64}
	Fire detectors (Two separate) (4)	b_{65}
	Firefighting facilities are electrically illuminated (4)	b_{66}
	Audible and visual alarms (4)	b_{67}
	Foam water spray system (4)	b_{68}
	Fire protection for main structure (4)	b_{69}
	Fire alarm controller (video type) (5)	b_{70}
	Fire engines (7)	b_{71}
Communication facilities B_9=b_{72}+b_{73}+…+b_{75} γ_9=7%	Emergency telephone facilities (20)	b_{72}
	Cablecast (27)	b_{73}
	FM radio (18)	b_{74}
	Signal coverage (one operator) (8) Signal coverage (two operators) (15) Signal coverage (three operators) (35)	b_{75}
Emergency management B_{10}=b_{76}+b_{77}+…+b_{83} γ_{10}=13%	No fire emergency plan (0) Fire emergency plan (general operationalization) (8) Fire emergency plan (operational) (20)	b_{76}
	No emergency computerized system (0) Emergency computerized system (partially) (8) Emergency computerized system (refinement) (16)	b_{77}
	Emergency facility linkage control (11)	b_{78}
	No emergency drills (0) Regular table-top exercises (7) Regular hands-on exercises (16)	b_{79}
	Training for rescuers (11)	b_{80}
	Crew arrival time at the fire ≤ 30min (3) Crew arrival time at the fire ≤ 10min (6)	b_{81}

[a] If the sub-guarantee factors meet national standards, the score for this item will be.

[b] If there are missing items in the sub-guarantee factors of long tunnels (tunnel clusters), and the missing assessment items do not need to be set by the requirements of the relevant specifications, the corresponding scores of the safeguard factors of the sub-item shall be full marks.

5 Application Examples

5.1 Assessment of the Basic Conditions of the Tunnel

The basic situation of a long tunnel on an expressway in Guizhou Province was obtained through research:

The tunnel is separated, and its design speed is 80km/h. The length of the tunnel in the upward direction is 4378m, for the downward direction is 4348m. The tunnel is equipped with a complete lighting and ventilation system. The main tunnel has a clear width of 10.25m and a clear height of 7.1m, the entrance is cutting bamboo type. The upward and downward horizontal alignment of the tunnel is located on a circular curve that meets a straight line, the radius of the circular curve of the tunnel is greater than the general value of 400 m. It has been verified that the tunnel is not on a continuous long steep downhill section. In 2023, the tunnel has 9.24 million vehicle kilometers of upstream traffic and 9.70 million vehicle kilometers of downstream traffic. Traffic volumes are 3,378 (pcu/d·ln) for the upstream lanes and 3,544 (pcu/d·ln) for the downstream lanes.

According to the latest civil engineering inspection report, the technical condition of the civil engineering structures of the tunnel is assessed as Category 2 for the upward and downward direction. According to the results of the latest mechanical and electrical inspection report, the technical condition of the mechanical and electrical structures was assessed as Category 2 for the upward and downward direction.

The tunnel is not congested and there have been no disaster-causing accidents in the past year. According to the tunnel's historical accident statistics, there have been no tunnel fire accidents since the tunnel opened to traffic. The tunnel has a complete emergency response plan for tunnel fires, and the management unit regularly organizes emergency response drills in the form of tabletop and real-life drills.

5.2 Fire Risk Assessment

The actual conditions of the tunnel were scored in both upward and downward directions according to the scoring principles in Table 2 and Table 3, the calculation results of the risk factor and guarantee factor are shown in Table 4 and Table 5.

Table 4. Tunnel risk factor scores.

Number	Risk factors	γ_i(%)	Upward	Downward
			F_i	F_i
1	Annual million kilometers	15	32	32
2	Lane traffic volume	15	36	36
3	Annual million kilometers of large cars	19	19	15
4	Transportation of dangerous goods	23	100	100
5	Tunnel linearity	12	0	0
6	Civil engineering	8	24	24
7	Other risks	8	7	7
8	$\sum_{i=1}^{n} \gamma_i F_i$	—	39.29	38.53
9	F	—	0.809	0.805

Table 5. Tunnel guarantee factor scores.

Number	Guarantee factors	γ_i(%)	Upward	Downward
			B_i	B_i
1	Ventilation facilities	10	46	64
2	Lighting facilities	9	100	77
3	Power supply facilities	10	74	74
4	Traffic monitoring facilities	10	100	100
5	Environmental monitoring facilities	7	85	85
6	Traffic control facilities	9	58	19
7	Escape and rescue facilities	11	70	70
8	Firefighting facilities	14	71	75
9	Communication facilities	7	55	82
10	Emergency management	13	75	72
11	B	—	73.41	71.69

Calculate the tunnel fire safety assessment value D according to equation (2):
upward direction: D=B/F=73.41/0.809=90.74
downward direction: D=B/F=71.69/0.805=89.06

Based on the calculated fire risk assessment value D of the tunnel, the risk level of the tunnel is determined according to Table 1: the fire risk level in the upward direction is Class I and the fire risk level in the downward direction is Class II. According to the risk classification and response measures, the upward direction has a low fire risk and no other risk control measures can be taken in addition to normal maintenance and operation; the downward direction has a general fire risk and it is appropriate to take preventive measures, such as key inspections, monitoring, and early warning, etc.

6 Conclusion

In this study, the fire accident risk sources of long tunnels on mountainous expressways are divided into risk factors and guarantee factors according to their impacts on fire accidents. Combined with the latest tunnel design and maintenance standards in the transportation industry, a detailed evaluation standard is formulated for the guarantee factor of mountainous expressway tunnels, and the values of the indicators are explained so that an assessment model of the fire accident factor of long tunnels on mountainous expressways is established. Through example calculations, the model helps tunnel operation and management units assess the risk level of tunnel fire accidents under their jurisdiction, to take targeted preventive management measures to improve traffic safety.

This study has several limitations. In the assessment of risk factors, the model only considers objective risk factors and is unable to consider subjective risk factors, such as vehicle factors and driver factors. This study determines the importance of the indicator by assigning different scores and weights to the indicator, but this study does not clearly identify the key factors affecting fire safety in tunnels, nor does it discuss the interactions between the indicators. In future, we will consider these limitations.

Acknowledgments

This paper is supported by the Science and Technology Program of Guizhou Provincial Department of Transportation "Guizhou Province Highway Project Safety Evaluation Guide" (2020-141-022).

References

1. Lin Z and Wu S (2016) Risk Assessment Methodology for Tunnel Operation Safety. China Highway, 05: 110-114.
2. Guo B, Han L and An C (2023) Research status and prospect of safety risk and disaster prevention and evacuation in large highway tunnel. Water Resources and Hydropower Engineering, 54(S1): 327-332.
3. Fu X, Yang Q and Liu H (2004) Discussion on the Safety Maneuver about Fire Prevention and Succor of Long Highway Tunnel. Journal of Highway and Transportation Research and Development, (03): 56-59+63.
4. Zeng L, Wang S and Lu H (2012) Fire Disaster Reduction and Emergency Management of Long Highway Tunnels. Chinese Journal of Underground Space and Engineering, 8(S1): 1584-1590+1625.
5. Król A, Król M (2021) Numerical investigation on fire accident and evacuation in a urban tunnel for different traffic conditions. Tunnelling and Underground Space Technology, 109:103751.
6. Santos-Reyes J and Beard AN (2017) An analysis of the emergency response system of the 1996 Channel tunnel fire. Tunnelling and Underground Space Technology, 65: 121-139.