Evaluation Techniques for Traffic Safety of Operating Highway Tunnels

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Abstract: With the consideration of frequent occurrence of traffic accidents on operating highway tunnels, the advancement of safety evaluation for highway tunnels in domestic and abroad are systematically summarized. Through the comprehensive analysis of infrastructure factors influencing on traffic safety of highway tunnels, safety checklists focusing on tunnel horizontal and vertical alignment, tunnel portal situation, pavement condition, ventilation and lighting facilities, traffic safety facilities are provided in qualitatively evaluating operating highway tunnels. Based on the concept of risk, risk assessment indices oriented in infrastructure factors, environmental factors and management factors for operation safety of expressway tunnels and standard highway tunnels are put forward. Quantitative evaluation methods based on indices architecture and the corresponding classification criteria for operation safety risk of tunnels are developed.

1 Preface

In recent years, with the development of national economy and the increasing demand of production and life, the highway transportation in China has developed rapidly, and the construction of highway tunnels has also made great achievements. By 2016, China had built 15,181 road tunnels with a total length of 14,039.7 kilometers, including 815 extra-long tunnels with 3,622.7 kilometers and 3,520 long tunnels with 6,045.5 kilometers. The tunnel belongs to the road section with abrupt change of road environment. The driver needs to deal with a large amount of information in the process of vehicle driving, which is easy to cause operational errors, resulting in the tunnel becoming a section with frequent traffic accidents. As an important means to prevent traffic accidents and reduce the severity of accidents, safety evaluation has been widely used in foreign countries. Therefore, combined with the relevant research results domestic and abroad, through the analysis of the factors affecting the safety of highway tunnel operation, the corresponding safety checklist is prepared, and the quantitative safety assessment methods based on risk assessment are proposed respectively for highway and standard highway tunnels, in order to provide technical support for the safety assessment of highway tunnels in service.

2 Analysis of research status domestic and abroad

In the world, tunnel safety has always been very concerned. In particular, European countries began to pay attention to the safety of tunnel operation after major fire accidents in Mont Blanc tunnel and Taun tunnel. According to the requirements of "Minimum requirements for tunnel safety in the trans European road network Directive 2004 / 54 / EC of the European Conference / Council of 29 April 2004", it is necessary to carry out safety assessment on the tunnel and set up a special organization eurotest to check and evaluate the risk degree and safety of the existing road tunnel in Europe. Generally speaking, the technology of highway tunnel safety evaluation in European countries has developed earlier and more mature, and the evaluation method is mainly the combination of quantitative and qualitative. But there are also some shortcomings, such as the imperfect evaluation index system, the less consideration of the impact on human behavior and organizational structure, and the weak operability.

The research on the safety evaluation of highway tunnels started late in China. At present, the research mainly focuses on the safety evaluation index system and evaluation methods of tunnel operation or the advanced methods and technologies of the European Union, applying the concepts of risk potential and safety potential. The Specifications for Highway Safety Audit (JTG B05-2015), which was officially implemented in April 2016, only made general regulations on the safety evaluation contents of the existing highway tunnels from the aspects of highway geometry, sight distance, pavement anti-sliding ability, cross section, electromechanical facilities, safety facilities, etc. The existing research results and industry norms are relatively shallow to the special safety evaluation of highway tunnels in service, and lack of detailed evaluation index system and corresponding qualitative and quantitative

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evaluation methods, which is difficult to meet the safety evaluation requirements of a single tunnel.

3 Evaluation method based on safety checklist

According to the basic principles of safety engineering, combined with the relevant research results domestic and abroad and the summary and refinement of some typical road tunnel accidents, the safety checklist is a list of problems affecting the traffic safety of tunnels based on the field investigation and observation of some tunnels. When carrying out safety evaluation for highway tunnels in service, according to the safety checklist for issue list, through the review of design documents, field reconnaissance, field test or inquiries related personnel from the tunnel horizontal alignment, vertical alignment, pavement, ventilation, lighting, such as traffic safety facilities for inspection, found the potential risk factors and potential safety hazard.

Table 1. Safety checklists for operating highway tunnel

Evaluation content	Evaluation means	Evaluation conclusion
1 horizontal alignment		
Is horizontal curve set in the tunnel? If it has to be set, is the flat curve radius without superelevation adopted and meets the requirements of stopping sight distance?	Evaluation according to design documents	
Is the exit direction of long and extra long tunnels connected with small radius horizontal curve?	Evaluation according to design documents	
2 vertical alignment		
Does the longitudinal slope of the tunnel consider traffic safety, operation ventilation scale and drainage requirements? Is it not less than 0.3% and not more than 3%?	Evaluation according to design documents	
Are there too many slope change points in the tunnel?	Evaluation according to design documents	
3 horizontal and vertical alignment of portal section		
Is the horizontal and vertical alignment consistent within the range of 3S design speed stroke length inside and outside the tunnel portal?	Evaluation according to design documents	
Is the tunnel entrance located near the slope change point of convex vertical curve?	Evaluation according to design documents	
Is the tunnel portal located in the section with long and steep downhill and small radius curve?	Evaluation according to design documents	
Is there a certain length of transition between the tunnel and the wiring outside the tunnel?	According to the design documents and site survey evaluation.	
Are emergency parking strips provided in long and extra long tunnels? Does the width of the emergency stop belt meet the requirements of safe parking for large trucks?	According to the design documents and site survey evaluation.	
4 road surface		
Does the tunnel pavement have good skid resistance?	According to the field test evaluation.	
When cement concrete is used in the tunnel and asphalt pavement is used outside the tunnel, is there a certain length of transition section?	According to the site survey evaluation	
Is the long and extra long tunnel equipped with color pavement within 50m of the entrance and exit?	According to site survey and evaluation.	
Will the tunnel pavement return to moisture under adverse weather conditions?	According to site survey and evaluation.	
5 ventilation facilities		
Does the tunnel ventilation design meet the requirements of current specifications?	Evaluation according to design documents.	
Does the tunnel ventilation system have the ventilation control function under normal and fire conditions?	Evaluation according to design documents.	
Is ventilation good? Is good visibility guaranteed in the tunnel?	According to site survey and evaluation.	
Is the ventilation equipment capable of resisting high temperature?	Evaluation according to design documents.	
Can the fan run in reverse?	According to field test evaluation.	
6 lighting facilities		

Does the tunnel lighting design meet the requirements of current specifications?	Evaluation according to design documents.	
Is the tunnel open normally? Is there emergency lighting?	According to site survey and evaluation.	
Can power supply be ensured in case of partial failure? Is there a continuous power system UPS?	According to site survey and evaluation.	
Is there an obvious "black and white hole" effect at the tunnel entrance?	According to site survey and evaluation.	
Whether the lighting fixtures are clean?	According to site survey and evaluation.	
7 traffic safety facilities		
Are tunnel signs, speed limit signs and no overtaking signs set before the tunnel entrance?	According to site survey and evaluation.	
When the tunnel is long, the traffic volume is large and located in the uphill road section, is lane indication sign set in front of the tunnel entrance?	According to site survey and evaluation.	
When the radius of horizontal curve in the tunnel is small, is there a linear guide sign or active luminous contour sign?	According to the design documents and site survey evaluation.	
Is the end wall of tunnel portal marked with facade mark?	According to site survey and evaluation.	
Is a zebra crossing in the direction of oblique traffic built in the hard shoulder 50m in front of the tunnel entrance?	According to site survey and evaluation.	
Is lane change forbidden at the boundary of carriageway 100m in front of the tunnel entrance and 50m behind the tunnel exit?	According to site survey and evaluation.	
Is the subgrade guardrail gradually transited to the end of the tunnel portal access road?	According to site survey and evaluation.	
In order to alleviate the "black hole" and "white hole" effects at the entrance and exit of the tunnel, are active light-emitting inducing facilities set up to realize the smooth transition of light and shade level inside and outside the tunnel?	According to site survey and evaluation.	
8 fire fighting and rescue facilities		
Is the number of fire extinguishers in accordance with fire regulations?	According to site survey and evaluation.	
Is the fire extinguisher in an open and fixed position and easy to use?	According to site survey and evaluation.	
Is the fire extinguisher dated? Is it regularly inspected and maintained?	According to site survey and evaluation.	
Does the fire hose and emergency broadcast system work normally?	According to the field test evaluation.	
Is the fire hydrant and fire pump adapter in good condition?	According to field test evaluation.	
Is there a fire water reservoir? Is there any accumulation and garbage in the pool?	According to site survey and evaluation.	
Is the emergency exit spacing reasonable?	Evaluate according to the design documents	
Is the emergency exit sign set? Is it clearly visible?	According to site survey and evaluation.	
Is the escape way provided with good smoke and fire protection function?	According to site survey and evaluation.	
Is there emergency lighting in the escape way?	According to site survey and evaluation.	
9 monitoring facilities		
Is there a tunnel monitoring center?	According to site survey and evaluation.	
Is the tunnel monitoring center manned 24 hours a day?	According to on-site inquiry and evaluation.	
Is vehicle detector installed? Is the vehicle detector intact?	According to site survey and evaluation.	

Can real-time monitoring of the whole tunnel be realized?	According to site survey and evaluation.	
Does the camera and video monitoring control equipment work normally?	Pass the field test evaluation。	
Is variable information board installed?	According to site survey and evaluation.	
Is there a radio broadcast in the whole tunnel?	According to site survey and evaluation.	
Is there an emergency phone? Are emergency telephone signs complete?	According to site survey and evaluation.	
10 other facilities		
Is the long and extra long tunnel provided with a connecting passage at a suitable position outside the tunnel entrance to facilitate vehicle turning around?	According to site survey and evaluation.	
For the road section with more heavy vehicles, does the cover strength of drainage side ditch and cable trench in the tunnel meet the requirements of vehicle driving?	Through the evaluation of design documents.	
When the tunnel exit is greatly affected by bad weather, such as heavy fog and snowfall, have targeted measures been taken?	According to site survey and evaluation.	

4 Evaluation method based on risk assessment

After many years of operation, some highway tunnels have some problems, such as the aging or defect of fire-fighting equipment, the failure of ventilation and lighting facilities to operate as required, the weak emergency rescue capacity, the inadequate management of dangerous goods transport vehicles, etc., which lead to a large potential safety hazard and traffic accidents. Therefore, in the process of tunnel operation, the concept of risk is introduced, the safety risk of tunnel operation is identified, and its qualitative and quantitative evaluation is carried out, which has attracted the attention of many researchers domestic and abroad, and qualitative and quantitative evaluation methods such as Delphi method, event tree method, checklist method, analytic hierarchy process, fuzzy comprehensive evaluation method are proposed.

4.1.Safety risk assessment of expressway tunnel operation

Because there are many risk factors that affect the safety of highway tunnel operation, some of them, such as driver and vehicle conditions, are difficult to quantify. In order to evaluate the safety risk of expressway tunnel operation accurately, it is necessary to extract the risk factors which are easy to quantitatively or qualitatively evaluate and have great influence on the safety risk of operation on the basis of safety risk identification, and then establish the corresponding risk assessment index system. Combined with the current situation of expressway tunnel operation safety in China and relevant research results domestic and abroad, the tunnel operation safety risk assessment index system as shown in Table 2. It is constructed from three aspects of facility factors, environmental factors and management factors.

Table 2. Risk assessment indices for operation safety of expressway tunnels

Factors	Evaluation index	Classification	Basic score (Rij)		weight coefficient(γ_{ij})	Evaluation score (T_{ij})
			Range of values	Value		
Facility factor T_1	Tunnel length T_{11}	L＞3000m	75-100	R_{11}	γ_{11}	$T_{11}=\gamma_{11}\times R_{11}$
		1000m＜L≤3000m	50-74			
		500m＜L≤1000m	25-49			
		L≤500m	0-24			
	Horizontal and vertical alignment combination of tunnel T_{12}	The combination of horizontal and vertical alignment is poor, and there is a serious potential safety hazard	75-100	R_{12}	γ_{12}	$T_{12}=\gamma_{12}\times R_{12}$
		The combination of horizontal and vertical alignment is unreasonable, and there is obvious potential safety hazard	50-74			
		Poor combination of horizontal and vertical alignment has certain impact on driving safety	25-49			
		Good combination of horizontal and vertical alignment	0-24			
	Skid	SFC＜0.3	75-100	R_{13}	γ_{13}	$T_{13}=\gamma_{13}\times R_{13}$

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	resistance of pavement T_{13}	0.3≤SFC＜0.4	50-74			
		0.4≤SFC＜0.5	25-49			
		SFC≥0.5	0-24			
	Safety facilities T_{14}	The tunnel section lacks corresponding safety protection, driving guidance and speed control facilities	75-100	R_{14}	γ_{14}	$T_{14}=\gamma_{14}\times R_{14}$
		The tunnel portal lacks necessary safety protection and speed control facilities	50-74			
		Lack of necessary driving guidance and prompt facilities in the tunnel	25-49			
		Perfect and reasonable traffic safety facilities in tunnel section	0-24			
	Tunnel lighting T_{15}	The lighting in the tunnel is not turned on	75-100	R_{15}	γ_{15}	$T_{15}=\gamma_{15}\times R_{15}$
		The tunnel lighting is poor, and there is obvious black and white hole effect at the tunnel entrance	50-74			
		The tunnel lighting is general, and there are some light and shade adaptation problems at the entrance of the tunnel	25-49			
		Good tunnel lighting	0-24			
	Emergency exit distance T_{16}	D＞650m	75-100	R_{16}	γ_{16}	$T_{16}=\gamma_{16}\times R_{16}$
		450m＜D≤650m	50-74			
		250m＜D≤450m	25-49			
		D≤250m	0-24			
	Monitoring facilities T_{17}	The monitoring facilities are not perfect and most of them cannot be used normally	75-100	R_{17}	γ_{17}	$T_{17}=\gamma_{17}\times R_{17}$
		The monitoring facilities are not perfect and some of them cannot be used normally	50-74			
		Some monitoring facilities cannot be used normally	25-49			
		Complete and reliable monitoring facilities	0-24			
environmental factor T_2	Annual average daily traffic volume of single tunnel T_{21}	AADT＞30000	75-100	R_{21}	γ_{21}	$T_{21}=\gamma_{21}\times R_{21}$
		10000＜AADT≤30000	50-74			
		4000＜AADT≤10000	25-49			
		AADT≤4000	0-24			
	Heavy truck ratio T_{22}	HGV＞50%	75-100	R_{22}	γ_{22}	$T_{22}=\gamma_{22}\times R_{22}$
		30%＜HGV≤50%	50-74			
		10%＜HGV≤30%	25-49			
		HGV≤10%	0-24			
	Climatic factors T_{23}	Frequent bad weather	75-100	R_{23}	γ_{23}	$T_{23}=\gamma_{23}\times R_{23}$
		More bad weather	50-74			
		Less bad weather	25-49			
		Almost no bad weather	0-24			
Management factors T_3	Accident rate per million vehicle kilometers T_{31}	CR＞0.50	75-100	R_{31}	γ_{31}	$T_{31}=\gamma_{31}\times R_{31}$
		0.30＜CR≤0.50	50-74			
		0.15＜CR≤0.30	25-49			
		CR≤0.15	0-24			
	Speed limit T_{32}	SL＞100km/h	75-100	R_{32}	γ_{32}	$T_{32}=\gamma_{32}\times R_{32}$
		80km/h＜SL≤100km/h	50-74			
		60km/h＜SL≤80km/h	25-49			
		SL≤60km/h	0-24			
	Emergency response time T_{33}	ERT＞20min	75-100	R_{33}	γ_{33}	$T_{33}=\gamma_{33}\times R_{33}$
		10＜ERT≤20min	50-74			
		5＜ERT≤10min	25-49			
		ERT≤5min	0-24			

	Dangerous goods vehicle management T_{34}	Permitted passage	75-100	R_{34}	γ_{34}	$T_{34}=\gamma_{34}\times R_{34}$
		Limitation of partial goods or quantity	50-74			
		Time limit	25-49			
		No passage at all	0-24			
		Limitation of partial goods or quantity	50-74			
		Time limit	25-49			
		No passage at all	0-24			

4.2. Operation safety risk assessment of standard highway tunnel

Since the overtaking tunnel or another tunnel can be used for traffic evacuation and escape in the event of an accident in the expressway tunnel, traffic organization and rescue escape will face greater problems in the event of an accident in the standard highway tunnel, therefore, it is necessary to evaluate the operation safety risk of the standard highway tunnel. Considering that compared with the expressway tunnel, the standard highway tunnel is poor in geometry, ventilation and safety management, on the basis of expressway tunnel operation safety risk evaluation index system, several evaluation indexes are added, and the evaluation index system of standard highway tunnel operation safety risk is proposed as shown in Table 3.

Table 3. Risk assessment indices for operation safety of standard highway tunnels

Factors	Evaluation index	Classification	Basic score (R_{ij}) Range of values	Basic score (R_{ij}) values	Weight coefficient (γ_{ij})	Evaluation score (T_{ij})
Facility factor T_1	Tunnel length T_{11}	L＞3000m	75-100	R_{11}	γ_{11}	$T_{11}=\gamma_{11}\times R_{11}$
		1000m＜L≤3000m	50-74			
		500m＜L≤1000m	25-49			
		L≤500m	0-24			
	Tunnel portal alignment T_{12}	The alignment inside and outside the tunnel portal is in very poor consistency	75-100	R_{12}	γ_{12}	$T_{12}=\gamma_{12}\times R_{12}$
		The alignment inside and outside the tunnel portal is in poor consistency	50-74			
		The alignment inside and outside the tunnel portal is in general consistency	25-49			
		The alignment inside and outside the tunnel portal is in good consistency	0-24			
	Longitudinal slope of tunnel T_{13}	2.5%＜G≤3%	75-100	R_{13}	γ_{13}	$T_{13}=\gamma_{13}\times R_{13}$
		2%＜G≤2.5%	50-74			
		1.5%＜G≤2%	25-49			
		G≤1.5%	0-24			
	Tunnel pavement condition T_{14}	Large area of obvious subsidence, uplift, pothole, damage, crack, overflow, ice and other conditions on the tunnel pavement seriously affect the traffic safety and may lead to traffic accidents	75-100	R_{14}	γ_{14}	$T_{14}=\gamma_{14}\times R_{14}$
		Large area of subsidence, uplift, pothole, damage, crack and serious ponding occur in the tunnel pavement, which affects the driving safety, and the low anti sliding coefficient causes vehicle slipping	50-74			
		Local subsidence, uplift, pit, damage, crack, slight ponding and other conditions of tunnel pavement may affect driving safety	25-49			
		Tunnel pavement in good condition	0-24			
	Traffic sign	Most of them are dirty, falling off	75-100	R_{15}	γ_{15}	$T_{15}=\gamma_{15}\times R_{15}$

	marking T_{15}	and missing, which affects driving safety				
		There are dirt, local falling off, loss, etc., which affect traffic safety	50-74			
		Dirty, incomplete, not obstructing traffic	25-49			
		intact	0-24			
	Tunnel lighting T_{16}	There is no lighting lamp in the tunnel or the lighting lamp is not turned on	75-100	R_{16}	γ_{16}	$T_{16}=\gamma_{16}\times R_{16}$
		The tunnel lighting is poor, and there is obvious “black and white hole” effect at the tunnel entrance	50-74			
		Tunnel lighting is general, and there are some light and shade adaptation problems at the entrance of the tunnel	25-49			
		Good tunnel lighting	0-24			
	Tunnel ventilation T_{17}	There is no ventilation facilities in the tunnel or the ventilation facilities cannot be opened normally	75-100	R_{17}	γ_{17}	$T_{17}=\gamma_{17}\times R_{17}$
		There are few ventilation facilities in the tunnel or some ventilation facilities are damaged	50-74			
		Some ventilation facilities in the tunnel are damaged	25-49			
		Ventilation facilities in the tunnel can be opened normally	0-24			
	Evacuation and rescue facilities T_{18}	There is no fire alarm and fire rescue facilities in the tunnel or the facilities cannot be used normally	75-100	R_{18}	γ_{18}	$T_{18}=\gamma_{18}\times R_{18}$
		There are only a few fire alarm and fire rescue facilities in the tunnel or some facilities cannot be used normally	50-74			
		Some fire alarm and fire rescue facilities in the tunnel cannot be used normally	25-49			
		Necessary fire alarm and rescue facilities shall be set in the tunnel	0-24			
	Monitoring facilitiesT_{19}	There is no monitoring facility in the tunnel or the monitoring facility cannot be used normally	75-100	R_{19}	γ_{19}	$T_{19}=\gamma_{19}\times R_{19}$
		There are only a few monitoring facilities in the tunnel or some of them cannot be used normally	50-74			
		Some monitoring facilities in the tunnel cannot be used normally	25-49			
		The monitoring facilities in the tunnel are relatively complete	0-24			
Environmental factors T_2	Annual average daily traffic volume T_{21}	AADT＞15000，The situation of mixed operation of locomotive and non locomotive is serious	75-100	R_{21}	γ_{21}	$T_{21}=\gamma_{21}\times R_{21}$
		6000＜AADT≤15000，The situation of mixed operation of locomotive and non locomotive is relatively serious	50-74			
		2000＜AADT≤6000，There are few cases of mixed operation of locomotive and non locomotive	25-49			
		AADT≤2000，The situation of mixed operation of locomotive and non locomotive is very seldom	0-24			
	Heavy vehicle percentage	HGV＞50%	75-100	R_{22}	γ_{22}	$T_{22}=\gamma_{22}\times R_{22}$
		30%＜HGV≤50%	50-74			

	T_{22}	10%＜HGV≤30%	25-49			
		HGV≤10%	0-24			
	Operating speed T_{23}	OS＞80km/h	75-100	R_{23}	γ_{23}	$T_{23}=\gamma_{23}\times R_{23}$
		60km/h＜OS≤80km/h	50-74			
		40km/h＜OS≤60km/h	25-49			
		OS≤40km/h	0-24			
	Climate factors T_{24}	The tunnel entrance is seriously affected by rain and snow	75-100	R_{24}	γ_{24}	$T_{24}=\gamma_{24}\times R_{24}$
		The tunnel portal is easily affected by rain, snow and other weather	50-74			
		The tunnel portal is generally not affected by rain, snow and other weather	25-49			
		The tunnel portal is seldom affected by rain, snow and other weather	0-24			
Management factors T_3	Safety publicity and education T_{31}	Tunnel management organizations seldom carry out safety publicity and education	75-100	R_{31}	γ_{31}	$T_{31}=\gamma_{31}\times R_{31}$
		Tunnel management agencies rarely carry out safety education	50-74			
		Tunnel management organizations regularly carry out safety publicity and education	25-49			
		Tunnel management organizations often carry out safety publicity and education	0-24			
	Daily patrol management T_{32}	The tunnel lacks daily inspection	75-100	R_{32}	γ_{32}	$T_{32}=\gamma_{32}\times R_{32}$
		Less daily inspection for Tunnels	50-74			
		Regular inspection of tunnels	25-49			
		Daily inspection on civil structure, mechanical and electrical facilities and fire-fighting facilities is in place	0-24			
	Information release capability T_{33}	No information release capability	75-100	R_{33}	γ_{33}	$T_{33}=\gamma_{33}\times R_{33}$
		Weak ability of information release	50-74			
		Have certain information release ability	25-49			
		Timely release of tunnel information	0-24			
	Dangerous goods vehicle managementT_{34}	No restrictions	75-100	R_{34}	γ_{34}	$T_{34}=\gamma_{34}\times R_{34}$
		Dangerous goods vehicles should be reported when passing	50-74			
		Partial shipment or quantity restriction	25-49			
		Limit passage time	0-24			
	Emergency rescue capability T_{35}	Poor emergency rescue capability	75-100	R_{35}	γ_{35}	$T_{35}=\gamma_{35}\times R_{35}$
		The emergency rescue capability is relatively poor	50-74			
		For traffic accidents, fire has a certain rescue ability	25-49			
		There is a complete rescue force and a complete emergency plan	0-24			

According to the risk assessment index system established in Table 2 and Table 3, the safety risk of tunnel operation is evaluated by the index system method. The safety risk of tunnel operation shall be determined according to formula (1) and (2).

$$R=\Sigma T_{ij} \tag{1}$$

$$T_{ij}=\gamma_{ij}\times R_{ij} \tag{2}$$

Where: T_{ij} - the evaluation score of the evaluation index, i=1,2,3; j=1,2,... ...n, n is the number of the corresponding class of evaluation index; R_{ij} -the basic score of the evaluation index. For the quantitative index, the value of the evaluation index can be obtained through design documents, field observation or field test, and the basic score can be calculated by linear interpolation method. For the qualitative index, it can be determined by the professional according to the engineering experience; γ_{ij} - weight coefficient of each evaluation index, generally, it is determined by the method of "determining the value of weight by ranking the importance of evaluation indicators", and the calculation formula(3) is as follows:

$$\gamma_{ij} = \frac{2n - 2m + 1}{n^2} \quad (3)$$

Where: n - number of evaluation index items; m - importance sequence number. $m \le n$.

Through expert consultation and discussion, the importance ranking of safety risk assessment indicators for expressway and standard highway tunnel operation is determined, and the weight coefficient of safety risk assessment indicators for expressway tunnel operation is calculated by formula (3) as shown in Table 4.

Table 4. Classification criteria for operation safety risk of tunnel

No	Evaluation indicators	Weight coefficient
1	Tunnel length T_{11}	0.14
2	Horizontal and vertical alignment combination of tunnel T_{12}	0.11
3	Skid resistance of pavement T_{13}	0.06
4	Safety facilities T_{14}	0.05
5	Tunnel lighting T_{15}	0.08
6	Emergency exit distance T_{16}	0.02
7	Monitoring facilities T_{17}	0.03
8	Annual average daily traffic volume of single tunnel T_{21}	0.13
9	Heavy truck ratio T_{22}	0.09
10	Climatic factors T_{23}	0.04
11	Accident rate per million vehicle kilometers T_{31}	0.12
12	Speed limit T_{32}	0.07
13	Emergency response time T_{33}	0.01
14	Dangerous goods vehicle management T_{34}	0.10

The weight coefficient of the risk assessment index of the operation safety of the standard highway tunnel can also be determined according to the similar process.

After the calculated value, the safety risk level of tunnel operation is determined according to Table 5.

Table 5. Classification criteria for operation safety risk of tunnel

Risk level	R
Grade IV (very high risk)	R＞80
Level III (high risk)	60＜R≤80
Level II (moderate risk)	40＜R≤60
Grade I (low risk)	R≤40

5 Conclusion

With the rapid development of highway tunnel construction in China, the safety situation of highway tunnel operation is not optimistic, so it is very urgent to evaluate the safety of highway tunnel in service. Combined with the research status of safety evaluation of highway tunnels domestic and abroad, the safety checklist of highway tunnels is compiled by summarizing and analyzing the facility factors that affect the traffic safety of highway tunnels in China. Based on the concept of risk, the evaluation index system of tunnel operation safety risk is formed from three aspects: facility factor, environment factor and management factor. The evaluation index system of operation safety risk and the quantitative evaluation method of tunnel operation safety based on the index system method are proposed for the expressway and standard highway respectively, which is used to carry out the special safety evaluation of highway tunnel in service and provide technical support for the daily management and maintenance work and safety self inspection of the tunnel operation management unit.

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