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Study on the Evaluation Method of Highway Tunnel Service Performance Based on the Analytic Hierarchy Process

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Abstract: Current specifications mainly evaluate the highway tunnel service performance in the operation period from the integrity or defect status of tunnel engineering structures and mechanical and electrical facilities, yet fail to fully take into account the durability of tunnel structures or facilities, traffic flow smoothness, riding comfort and other performance dimensions. Therefore, by adopting research methods including literature research, theoretical analysis and expert investigation, an evaluation indicator system for the highway tunnel service performance was established based on the Analytic Hierarchy Process (AHP), and calculation models for each indicator were constructed, thus ultimately realizing the quantitative evaluation of tunnel service performance. Finally, based on the data of 33 ordinary highway tunnels in Shandong Province in 2025, the service performance scores of these tunnels were calculated, and the tunnels were ranked by maintenance priority according to the calculation results. This research provides an important basis for the maintenance decision-making of ordinary highway tunnels in Shandong Province.

Keywords: Highway tunnel; Service performance; Analytic hierarchy process; Maintenance decision

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1. Introduction

At present, China's highway tunnel industry has stepped into a new stage of equal emphasis on construction and maintenance [1]. A large number of highway tunnels opened to traffic in the early years have encountered problems such as the attenuation of service performance, prominent diseases in structures and facilities, and reduced traffic comfort [2]. Maintenance and management agencies of highway tunnels typically formulate maintenance strategies for tunnels within their jurisdiction based on the outcomes of routine inspections and technical condition evaluations. However, in accordance with *Technical Specification for Highway Tunnel Maintenance* (JTG H12-2015), the scope of such routine inspections and technical condition evaluations is mainly limited to assessing the integrity or defect status of tunnel structures and mechanical and electrical facilities, while failing to fully account for critical aspects including the durability of tunnel structures and facilities, traffic flow smoothness, and riding comfort. Therefore, it is essential to establish a service performance evaluation method for highway tunnels that can comprehensively characterize the safety, durability, traffic flow smoothness and riding comfort of the tunnel, thereby enabling a holistic assessment of the actual operation status of highway tunnels.

A large number of scholars have conducted a certain amount of research on the theories, indicators and methods of highway tunnel service performance evaluation. Dongping Li systematically elaborated the factors influencing the variation of highway tunnel service performance, as well as the geological and hazard problems existing in the service process of highway tunnels [3]. Chao Liu et al. summarized a systematic set of evaluation indicators for highway tunnel service performance from the three core dimensions of tunnel investigation, design and construction, and subsequently established a tunnel service performance evaluation method grounded in fuzzy theory [4]. Fang Xu identified the evaluation indicators for highway tunnel service performance using the improved TOPSIS method, and subsequently established an evaluation model for highway tunnel service performance grounded in Bayesian network theory [5]. Hehua Zhu and Xuezeng Liu developed a set of rapid identification equipment for tunnel structural defects and diseases, and further established an analysis platform for the service performance of highway tunnel structures based on a digital model-driven integrated numerical simulation and analysis methodology, which enables efficient performance analysis of highway tunnel structures [6]. Changhou Li et al. established an evaluation method for the long-term service performance of highway tunnels accounting for time-varying effects, on the basis of the time-varying degradation behavior of tunnel lining bending stiffness [7]. This method delivers a solid theoretical foundation for the long-term performance prediction of highway tunnel service performance. Li Yu et al. established a systematic evaluation indicator system from the perspective of operational safety and riding comfort of long-distance continuous tunnel clusters, and further extended and enriched the connotation and defined scope of highway tunnel service performance [8]. Yue Yang et al. additionally accounted for key factors including the operational performance of mechanical and electrical facilities, traffic environment, and safety management conditions, and subsequently established a systematic set of operational safety evaluation indicators for expressway tunnels [1]. Fayou Deng, Caichu Xia and Chongbang Xu proposed a health status evaluation method for highway tunnels grounded in neutrosophic theory, which overcomes the inherent limitation of the evaluation methods specified in the current valid specifications: their inability to implement robust service performance evaluation of highway tunnels under uncertain service conditions [9]. Huajie Zhu accounted for eight key influencing factors, namely traffic volume, precipitation, incline and vertical shafts, adverse geological conditions, lane count, service life post opening, tunnel length, and technical condition rating of tunnel structures, and subsequently established a systematic health status evaluation indicator system for operational expressway tunnels [10].

Most existing studies on the service performance evaluation of highway tunnels have predominantly focused on the defects and diseases of tunnel structures, whereas insufficient consideration has been given to the operational performance of mechanical and electrical facilities, the durability of tunnel structures and facilities, traffic flow smoothness, and riding comfort. To address this research gap, this study adopts a holistic perspective, fully accounts for four core evaluation dimensions including safety, durability, traffic flow smoothness and riding comfort, develops a comprehensive and systematic evaluation indicator system for highway tunnel service performance on the basis of the Analytic Hierarchy Process (AHP), establishes calculation models for each individual indicator, and ultimately proposes a complete evaluation methodology for the service performance of highway tunnels.

2. Evaluation indicators and calculation models of service performance

The evaluation indicators for the highway tunnel service performance should be selected based on society's demands for highway tunnels as an infrastructure. On the premise of striving for comprehensiveness and perfection, principles such as rigor, conciseness and highlighting key points should also be taken into account [11]. Based on a systematic literature review, societal demands for highway tunnels can be classified into the following four hierarchical dimensions: "safety", "durability", "traffic flow smoothness", and "riding comfort". Focusing on the aforementioned four hierarchical demand dimensions, the first-level evaluation indicators for highway tunnel service performance can be classified into four categories: Safety Indicator, Durability Indicator, Traffic Flow Smoothness Indicator, and Riding Comfort Indicator. The schematic diagram of the first-level evaluation indicator system is presented in **Figure 1**.

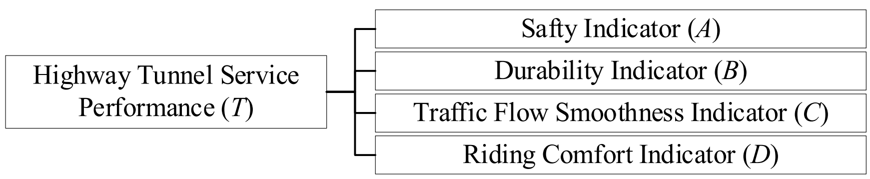

Figure 1. First-level evaluation indicator system for highway tunnel service performance.

Based on the Analytic Hierarchy Process (AHP), the calculation model for the service performance score T of highway tunnels is established, as shown in Equation (1). Herein, a, b, c and d represent the weights of the four first-level indicators, respectively. Considering that the public holds different expectations for tunnels of various highway classifications in terms of safety, durability, traffic smoothness and riding comfort, the value-taking criteria for the four weights are thus defined as presented in **Table 1**.

$$T = a \times A + b \times B + c \times C + d \times D \tag{1}$$

Table 1. Weight value-taking for first-level indicators of highway tunnel service performance

Weight of indicator \ Highway classification	Class I	Class II
Weight of safety indicator (a)	0.40	0.50
Weight of durability indicator (b)	0.30	0.30
Weight of traffic flow smoothness indicator (c)	0.20	0.15
Weight of riding comfort indicator (d)	0.10	0.05

2.1. Safety indicator

Numerous factors influence the safety of highway tunnels. From a macro perspective, compliance with highway tunnel technical standards (i.e., the conformity between the actual configuration of structures or facilities and the current technical standards), structural safety and facility safety are all key factors affecting the overall safety of highway tunnels. Thus, the Safety Indicator can be further divided into Technical Standard Compliance Indicator, Structural Safety Indicator and Facility Safety Indicator (as shown in **Figure 2**).

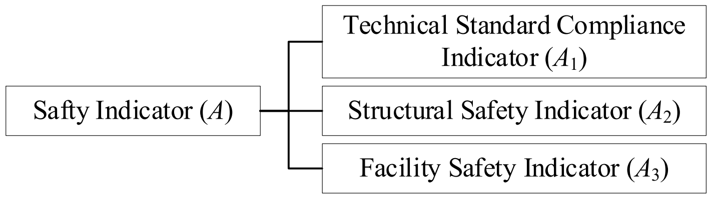

Figure 2. Safety Indicator system for highway tunnels.

The calculation model for Safety Indicator is shown in Equation (2), where a_i denotes the weight corresponding to each of the three second-level indicators. Considering the influence of tunnel length on the safety indicator, the value assignment of the weights is presented in **Table 2** (For long and extra-long tunnels, the structural and facility safety is of vital importance to the overall safety of the tunnel, and thus relatively higher values are assigned to a_2 and a_3).

$$A = \sum_{i=1}^{3} a_i \times A_i \tag{2}$$

Table 2. Weight value-taking for safety indicator of highway tunnels

Type of tunnel / Weight of indicator	Short tunnel	Medium tunnel	Long tunnel	Extra-long tunnel
Weight of technical standard compliance Indicator (a_1)	0.40	0.30	0.20	0.10
Weight of structural safety indicator (a_2)	0.30	0.35	0.40	0.45
Weight of facility safety indicator (a_3)	0.30	0.35	0.40	0.45

2.1.1. Technical standard compliance indicator

Technical standard compliance indicator assesses the conformity between the actual configuration of tunnel structure or facilities and the prevailing technical standards, and is composed of two sub-indicators: Technical Standard Compliance Indicator for Tunnel Structure and Technical Standard Compliance Indicator for Mechanical and Electrical Facilities. Of these, Technical Standard Compliance Indicator for Tunnel Structure is composed of Compliance Indicator for Cross Channel Spacing, Compliance Indicator for Drainage Ditch Layout, Compliance Indicator for Tunnel Alignment, Compliance Indicator for Construction Clearance, and Compliance Indicator for Maintenance Walkway Height; the Technical Standard Compliance Indicator for Mechanical and Electrical Facilities is composed of Compliance Indicator for Power Supply and Distribution Facilities Configuration, Compliance Indicator for Lighting Facilities Configuration, Compliance Indicator for Ventilation Facilities Configuration, Compliance Indicator for Fire Fighting Facilities Configuration, and Compliance Indicator for Monitoring and Communication Facilities Configuration. The Technical Standard Compliance Indicator system is shown in **Figure 3**. The calculation model for A_1 is presented in Equation (3). Given that the tunnel structure and mechanical and electrical facilities are of equal importance, an identical weight of 0.5 is assigned to both secondary indicators. The calculation models for A_{11} and A_{12} can be uniformly expressed by Equation (4), and the tertiary indicators along with their corresponding weight values are listed in **Table 3**.

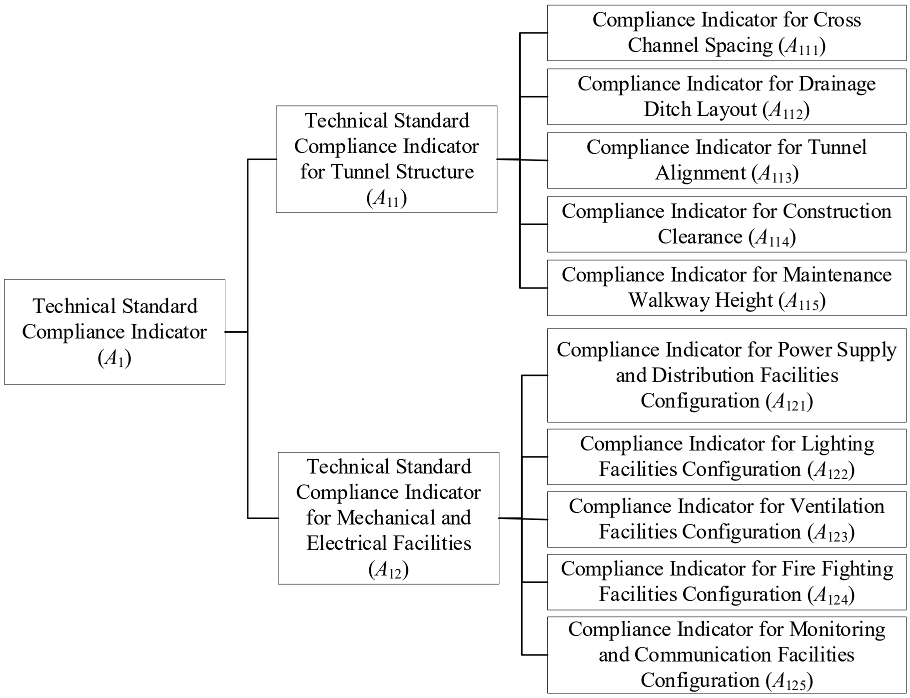

Figure 3. Technical standard compliance indicator system.

$$A_1 = 0.5 \times A_{11} + 0.5 \times A_{12} \tag{3}$$

$$A_{1i} = \sum_{i=1}^{2} \sum_{j=1}^{5} a_{1ij} \times A_{1ij} \tag{4}$$

Table 3. Technical standard compliance indicators and their corresponding weight values

Secondary indicator	Tertiary indicator	Weight	Indicator values		
			Fully compliant	Basically compliant	Non-compliant
A_{11}	A_{111}	0.2	1	0.8	0.5
	A_{112}	0.2	1	0.8	0.5
	A_{113}	0.2	1	0.8	0.5
	A_{114}	0.2	1	0.8	0.5
	A_{115}	0.2	1	0.8	0.5
A_{12}	A_{121}	0.23	1	0.8	0.5
	A_{122}	0.18	1	0.8	0.5
	A_{123}	0.19	1	0.8	0.5
	A_{124}	0.21	1	0.8	0.5
	A_{125}	0.19	1	0.8	0.5

2.1.2. Structural safety indicator

Structural Safety Indicator is designed to assess the safety status of tunnel structure and affiliated engineering facilities. In accordance with the *Technical Specifications for Highway Tunnel Maintenance* (JTG H12-2015), this indicator can be further decomposed into two subordinate indicators: Technical Condition Indicator and

Special Inspection Indicator. Specifically, Technical Condition Indicator is characterized by the results of the technical condition assessment for tunnel structure and affiliated engineering facilities. Correspondingly, Special Inspection Indicator, as a subordinate evaluation dimension, is composed of three tertiary indicators: Crack Condition Indicator, Water Leakage Condition Indicator, and Lining and Surrounding Rock Condition Indicator. Structural Safety Indicator system is presented in **Figure 4**. The calculation model for Indicator A_2 is specified in Equation (5). Tunnel operation and maintenance units routinely conduct qualitative and quantitative evaluation of tunnel structure safety based on periodic inspection and technical condition assessment results, while special inspection results are usually adopted as a supplementary approach to enrich the data pool and evaluation dimensions for tunnel structure safety assessment. On the basis of literature review and expert consultation, the two secondary indicators are assigned a weight of 0.8 and 0.2 respectively.

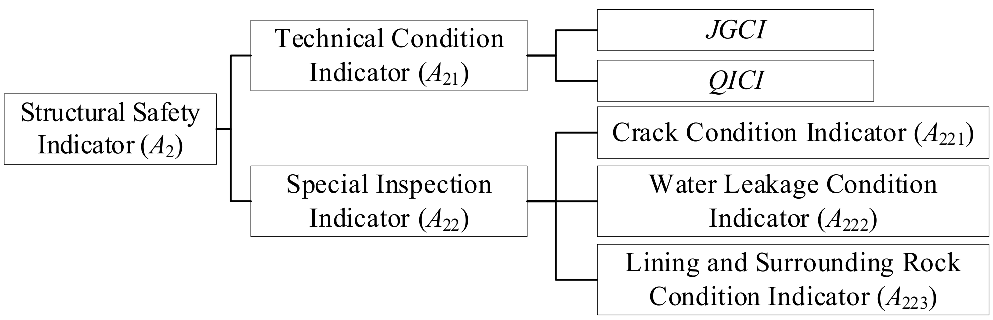

Figure 4. Structural safety indicator system.

$$A_2 = 0.8 \times A_{21} + 0.2 \times A_{22} \tag{5}$$

The calculation model for indicator A_{21} is specified in Equation (6). In this formula, *JGCI* represents the technical condition score of tunnel structure, while *QTCI* represents the technical condition score of affiliated engineering facilities. Considering that the safety performance of tunnel structure exerts a dominant influence on the overall safety of the highway tunnel, the weight of the technical condition score for tunnel structures is determined as 0.8, and the weight for the technical condition score of affiliated engineering facilities is set to 0.2 accordingly.

$$A_{21} = 0.8 \times JGCI + 0.2 \times QTCI \tag{6}$$

The calculation model for indicator A_{22} is specified in Equation (7). On the basis of systematic literature review and expert consultation, the three tertiary indicators are assigned weights of 0.4, 0.4 and 0.2 respectively, in accordance with their contribution to the tunnel structural safety evaluation.

$$A_{22} = 0.4 \times A_{221} + 0.4 \times A_{222} + 0.2 \times A_{223} \tag{7}$$

To quantify the indicator values of Crack Condition Indicator A_{221} and Water Leakage Condition Indicator A_{222} (both tertiary indicators under the Special Inspection Indicator), two core parameters are systematically defined: the crack density of the tunnel lining (pavement) is the ratio of the total number of cracks detected in the lining (pavement) to the total length of the tunnel, and the water leakage density of the tunnel lining (pavement) is defined in the same manner as the ratio of the total number of water leakage points in the lining (pavement) to the tunnel length. The indicator values are determined based on the correlation between the actual defect density of the target tunnel and the mean defect density of the baseline sample (shown in **Table 4**). Finally, the final value of indicator A_{221} is calculated as the product of the lining crack density indicator value and the pavement crack density indicator value, while the final value of indicator A222 is calculated as the product of the lining water leakage density indicator value and the pavement water leakage density indicator value.

Table 4. Indicator values for crack condition and water leakage condition

Indicator	Defect density is zero	Defect density between 0 and the mean defect density	Defect density is greater than the mean defect density
Value of lining crack density	1	0.8	0.5
Value of pavement crack density	1	0.8	0.5
Value of lining water leakage density	1	0.8	0.5
Value of pavement water leakage density	1	0.8	0.5

As a tertiary indicator under the Special Inspection Indicator system, Lining and Surrounding Rock Condition Indicator A_{223} is quantified by comprehensively incorporating five subordinate evaluation factors: lining thickness and compactness (A_{2231}), thickness of the lining's concrete cover (A_{2232}), surrounding rock classification(A_{2233}), compactness of the invert filling layer (A_{2234}), and karst development condition beneath the invert filling layer (A_{2235}). The calculation model for Indicator A_{223} is specified in Equation (8), with the detailed value determination standards for each of its subordinate indicators listed in **Table 5**.

$$A_{223} = \sum 0.2 \times A_{223i} \tag{8}$$

Table 5. Indicator values for lining and surrounding rock condition

Indicator	Indicator value	Scoring criteria
A_{2231}	1	The pass rate for lining thickness reaches 90% or higher, and the lining is free of defects such as voids or lack of compaction
	0.5	The pass rate for lining thickness is less than 90%, or the lining has defects such as voids or lack of compaction
A_{2232}	1	The concrete cover thickness for the reinforcing bars in the tunnel's lining meets the original design specifications.
	0.5	In some sections of the tunnel, the cover thickness of the lining reinforcement does not meet the original design specifications.
A_{2233}	1	The tunnel borehole rock mass consists primarily of Class I, II, and III rock.
	0.8	The tunnel borehole rock mass consists primarily of Class IV rock
	0.5	The tunnel borehole rock mass consists primarily of Class V and VI rock
A_{2234}	1	The infill layer of the tunnel's invert is dense and free of defects.
	0.5	The backfill layer of the tunnel invert is not compacted or contains defects
A_{2235}	1	There is no karst beneath the tunnel invert fill
	0.5	There is karst formation beneath the tunnel invert fill layer

2.1.3. Facility safety indicator

Similar to Structural Safety Indicator, Facility Safety Indicator is used to assess whether there are any safety hazards in the tunnel's mechanical and electrical facilities during operation. According to the

Technical Specifications for Highway Tunnel Maintenance (JTG H12-2015), Facility Safety Indicator can be further categorized into Technical Condition Indicator and Special Inspection Indicator. Technical Condition Indicator is characterized by the assessment results of the technical condition of power supply and distribution facilities, lighting facilities, ventilation facilities, firefighting facilities, and monitoring and communication facilities; whereas Special Inspection Indicator consists of Lightning Protection and Grounding Indicator, Firefighting Facilities Indicator, Suspended Load-Bearing Capacity Indicator, and High-Voltage Facilities Indicator. Facility Safety Indicator system is shown in **Figure 5**. The calculation model for indicator A_3 is shown in Equation 9 (based on expert survey results, the weights assigned to indicator A_{31} and A_{32} are 0.7 and 0.3, respectively).

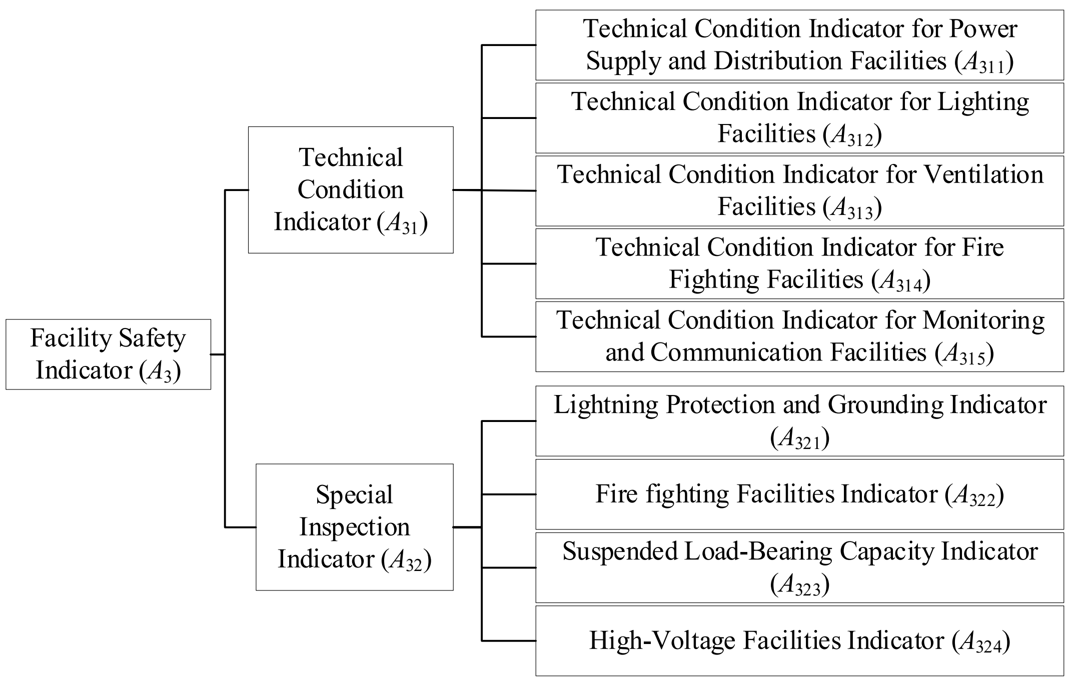

Figure 5. Facility safety indicator system.

$$A_3 = 0.7 \times A_{31} + 0.3 \times A_{32} \tag{9}$$

The calculation model for indicator A_{31} is shown in Equation 10. According to the *Technical Specifications for Highway Tunnel Maintenance* (JTG H12-2015), the weighting values for the five sub-indicators are shown in **Table 6**.

$$A_{31} = \sum_{i=1}^{5} a_{31i} \times A_{31i} \tag{10}$$

Table 6. Weighted values for technical condition indicator of mechanical and electrical facilities

Weight of Technical condition indicator for power supply and distribution facilities	Weight of technical condition indicator for lighting facilities	Weight of technical condition indicator for ventilation facilities	Weight of technical condition indicator for firefighting facilities	Weight of technical condition indicator for monitoring and communication facilities
0.23	0.18	0.19	0.21	0.19

The calculation model for indicator A_{32} is shown in Equation 11 (based on the results of expert surveys, the weights of the four sub-indicators were all set to 0.25); the scoring criteria for the four sub-indicators are shown in **Table 7**.

$$A_{32} = 0.25 \times \sum_{i=1}^{4} A_{32i} \tag{11}$$

Table 7. Scoring criteria for special inspection indicators for mechanical and electrical facilities

Indicator	Indicator value	Scoring criteria
A_{321}	1	A special initiative was launched and has yielded positive results.
	0.8	Special initiatives were launched, but the results were mixed.
	0.5	Special initiatives were launched, but the results were disappointing
	0	No specific initiatives have been undertaken
A_{322}	1	A special initiative was launched and has yielded positive results.
	0.8	Special initiatives were launched, but the results were mixed.
	0.5	Special initiatives were launched, but the results were disappointing
	0	No specific initiatives have been undertaken
A_{323}	1	A special initiative was launched and has yielded positive results.
	0.8	Special initiatives were launched, but the results were mixed.
	0.5	Special initiatives were launched, but the results were disappointing
	0	No specific initiatives have been undertaken
A_{324}	1	A special initiative was launched and has yielded positive results.
	0.8	Special initiatives were launched, but the results were mixed.
	0.5	Special initiatives were launched, but the results were disappointing
	0	No specific initiatives have been undertaken

2.2. Durability indicator

The overall durability of a tunnel is composed of the durability of tunnel structure and mechanical and electrical facilities. Further analysis reveals that the durability of tunnel structure is influenced by the strength of the lining, the depth of carbonation, and the corrosion of reinforcing bars; therefore, Durability Indicator of Tunnel Structure can be composed of Lining Strength Indicator, Carbonation Depth Indicator, and Reinforcing Bar Corrosion Indicator. Durability Indicator for Mechanical and Electrical Facilities consist of Pavement Brightness Indicator and Equipment Corrosion Indicator. Consequently, Durability Indicator system is shown in **Figure 6**.

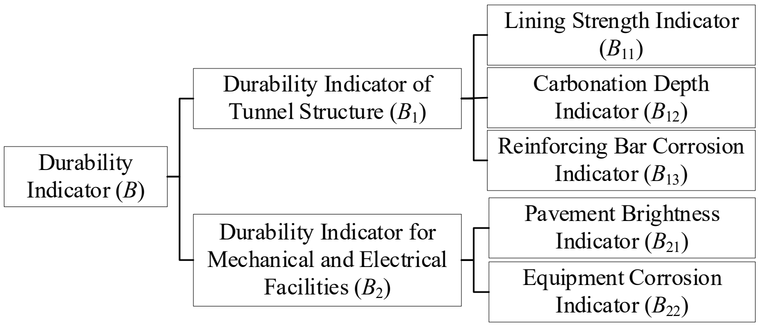

Figure 6. Durability indicator system for highway tunnels.

The calculation model for indicator B is shown in Equation 12 (since the durability of tunnel structure and mechanical and electrical equipment has an equal impact on the overall durability of the tunnel, the weight for both indicators is set to 0.5).

$$B = 0.5 \times B_1 + 0.5 \times B_2 \tag{12}$$

The calculation model for indicator B_1 is shown in Equation 13, and the scoring criteria for its sub-index are shown in **Table 8** (where K_C is the ratio of the average carbonation depth of the component to the average cover thickness of that type of component).

$$B_1 = 0.4 \times B_{11} + 0.2 \times B_{12} + 0.4 \times B_{13} \tag{13}$$

Table 8. Scoring criteria for durability indicator of tunnel structure

Indicator	Indicator value	Scoring criteria
B_{11}	1	The strength of the tunnel lining meets the design values
	0.5	There are sections of the tunnel where the lining strength is less than the design value.
B_{12}	1	$K_C < 0.5$
	0.8	$0.5 \le K_C < 1.0$
	0.6	$1.0 \le K_C < 1.5$
	0.4	$1.5 \le K_C < 2.0$
	0.2	$K_C \ge 2.0$
B_{13}	1	There is no evidence of reinforcing bar corrosion in the tunnel lining.
	0.5	The tunnel lining exhibits signs of reinforcing bar corrosion.

The calculation model for indicator B_2 is shown in Equation 14. Indicator B_{21} is calculated based on the inspection results of each lighting section on-site and the design requirements; its calculation model is shown in Equation 15, and its scoring criteria are listed in **Table 9**.

$$B_2 = 0.7 \times B_1 + 0.3 \times B_2 \tag{14}$$

$$B_{21} = \frac{\sum_{i=1}^{n} B_{21i}}{n} \tag{15}$$

Table 9. Scoring criteria for pavement brightness indicator

Indicator	Indicator value	Scoring criteria for the value of each randomly selected lighting section
B_{21}	1	Measured brightness value / Design value ≥ 1.3
	0.8	1 ≤ measured brightness value / design value < 1.3
	0.5	Measured brightness value / Design value < 1

The criteria for the value of indicator B_{22} are shown in **Table 10**.

Table 10. Scoring criteria for equipment corrosion indicator

Indicator	Indicator value	Scoring criteria
B_{22}	1	All mechanical and electrical equipment is free of corrosion
	0.8	Some mechanical and electrical equipment shows slight signs of corrosion
	0.5	There is severe corrosion of the mechanical and electrical equipment

2.3. Traffic flow smoothness indicator

Tunnel flow smoothness can be characterized by traffic volume and travel speed. On the one hand, if the actual traffic volume is less than the design traffic volume, the tunnel's flow smoothness is considered good; conversely, it is considered poor. On the other hand, if the actual travel speed within the tunnel is faster than the design speed or the speed limit, the tunnel's flow smoothness is considered good; conversely, it is considered poor. Based on this, the Traffic Flow Smoothness Indicator system is shown in **Figure 7**. The calculation model for indicator C is shown in Equation 16, and the scoring criteria for c_1 and c_2 are shown in **Table 11**. The scoring criteria for C_1 and C_2 are shown in **Table 12**.

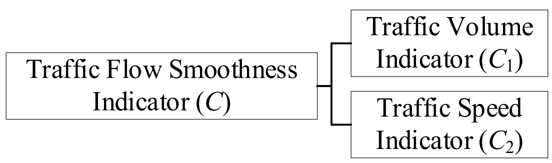

Figure 7. Traffic flow smoothness indicator system.

$$C = \sum_{i=1}^{2} c_i \times C_i \quad (16)$$

Table 11. Weighted values for traffic flow smoothness indicator

Tunnel type / Weight of indicator	Short tunnel	Medium tunnel	Long tunnel	Extra-long tunnel
Weight of traffic volume indicator (c_1)	0.90	0.80	0.70	0.60
Weight of traffic speed indicator (c_2)	0.10	0.20	0.30	0.40

Table 12. Scoring criteria for traffic flow smoothness indicator

Indicator	Indicator value	Scoring criteria
C_1	1	Actual traffic volume / Design traffic volume ≤ 1
	0.8	1 < Actual traffic volume / Design traffic volume ≤ 1.2
	0.5	Actual traffic volume / Design traffic volume > 1.2
C2	1	Actual speed / Design speed (or speed limit) > 1.2
	0.8	1 < Actual speed / design speed (or speed limit) ≤ 1.2
	0.5	Actual speed / Design speed (or speed limit) ≤ 1

2.4. Riding comfort indicator

Riding Comfort Indicator consist of Pavement Riding Comfort Indicator, Lighting Environment Comfort Indicator, and Improvement and Renovation Indicator; Riding Comfort Indicator system is shown in **Figure 8**. The calculation model for indicator D is shown in Equation 17; the scoring criteria for d_1, d_2, and d_3 are listed in **Table 13**, and those for D_1, D_2, and D_3 are listed in **Table 14**.

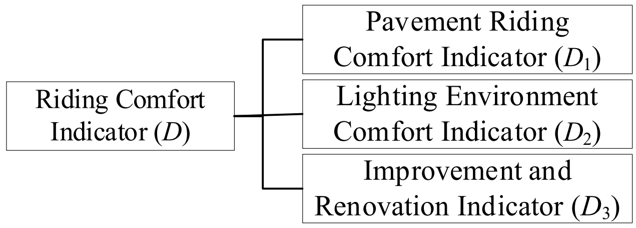

Figure 8. Riding Comfort Indicator system.

$$D = \sum_{i=1}^{3} d_i \times D_i \tag{17}$$

Table 13. Weighted values for riding comfort indicator

Tunnel type / Weight of indicator	Short tunnel	Medium tunnel	Long tunnel	Extra-long tunnel
Weight of pavement riding Comfort indicator (d_1)	0.30	0.40	0.40	0.50
Weight of lighting Environment comfort Indicator (d_2)	0.30	0.30	0.40	0.40
Weight of improvement and renovation indicator (d_3)	0.40	0.30	0.20	0.10

Table 14. Scoring criteria for riding comfort indicator

Indicator	Indicator value	Scoring criteria
D_1	1	PQI ≥ 95
	0.9	90 ≤ PQI < 95
	0.8	80 ≤ PQI < 90
	0.7	70 ≤ PQI < 80
	0.6	60 ≤ PQI < 70
	0.5	50 ≤ PQI < 60
D_2	1	Overall Uniformity of Pavement Brightness ≥ 0.4
	0.8	0.3 ≤ Overall Uniformity of Pavement Brightness < 0.4
	0.5	Overall Uniformity of Pavement Brightness < 0.3
D_3	1	Improvement projects designed to enhance riding comfort have been carried out.
	0.5	No projects have been carried out to improve riding comfort.

3. Engineering case study

33 highway tunnels in Shandong Province were selected. Data on the tunnels' basic information, operational management, structure and facilities, as well as the results of the 2025 technical condition assessment, were collected. Using calculation models of service performance introduced above, service performance scores were calculated for all 33 tunnels. Based on these results, the tunnels were ranked in order of maintenance priority (the lower the service performance score, the poorer the service performance, the higher the maintenance priority). Because a large amount of data was used in the calculations, **Table 15** shows only the results and a portion of the data.

Table 15. 2025 Shandong province highway tunnel service performance scoring and maintenance priority ranking

Tunnel name	Tunnel length (m)	Jgci	Qtci	Service performance scoring	Maintenance priority ranking
Dongfeng tunnel (Right)	50	79.5	98.33	73.37	1
Dongfeng tunnel (Left)	50	77.75	98.33	73.6	2
Pingyindong tunnel (Left)	360	70	98.55	74.01	3
Pingyindonga tunnel (Right)	360	71.25	98.55	74.29	4
Pingyin tunnel (Left)	440	77.5	100	76.56	5
Pingyin tunnel (Right)	440	77.5	100	76.56	6
Yiheyuan tunnel	126	74.75	100	77.44	7
Taojiakuang tunnel (Right)	1440	73.5	100	80.66	8
Huangshan tunnel (Right)	498	76.75	100	80.73	9
Huangshan tunnel (Left)	495	80.5	100	81.09	10
Taojiakuang tunnel (Left)	1000	78.5	100	81.19	11
Dongkuang tunnel (Right)	965	73.75	100	81.33	12
Wuyan tunnel (Right)	350	81.25	100	81.72	13
Dongkuang tunnel (Left)	960	73.75	100	81.89	14
Pizishan tunnel (Left)	455	79.75	100	82.61	15
Pizishan tunnel (Right)	456.5	78.75	100	82.68	16
Huangjiakuang tunnel (Right)	580	79	100	83.74	17
Huangjiakuang tunnel (Left)	580	74.5	100	83.76	18
Wuyan tunnel (Left)	360	76.25	100	83.84	19
Puqiuling tunnel	390	79	91.67	85	20
Songxianling tunnel	446	77.5	100	85.21	21
Yunmenshan tunnel (Left)	432	76.75	100	85.56	22
Yunmenshan tunnel (Right)	432.3	77.5	100	85.9	23
Shibapan tunnel	590	80.25	100	86	24
Magongci tunnel	735	77.75	100	87.75	25
Tuoshan tunnel (Right)	330	77.5	100	87.81	26
Tuoshan tunnel (Left)	331.7	78.75	100	87.9	27
Shuishiling tunnel	650	81.75	100	88.56	28
Chenyuling tunnel	528	80.25	100	89.24	29
Yangkou tunnel (Right)	3880	77.75	100	89.97	30
Yangkou tunnel (Left)	3880	77.75	100	90.43	31
Shuangdingshan tunnel	485	72.25	91.67	91.44	32
Mashidian tunnel	275	73.5	100	91.82	33

4. Conclusion

Through this study, the following conclusions can be drawn:

(1) Highway tunnel service performance can be evaluated in terms of safety, durability, traffic flow smoothness, and riding comfort. Specifically, the safety evaluation should consider compliance with technical standards as well as the safety of tunnel structures and facilities; the durability evaluation

should take into account both the durability of tunnel structure and mechanical and electrical facilities; and traffic flow smoothness can be assessed in terms of both traffic volume and travel speed. and the evaluation of riding comfort should comprehensively consider the comfort of the pavement and lighting environment, as well as the status of tunnel upgrades and renovations.

(2) A calculation model for highway tunnel service performance established based on the Analytic Hierarchy Process (AHP) enables the quantitative calculation and evaluation of service performance during the operational phase, thereby avoiding the shortcomings of subjective qualitative evaluations; simultaneously, the calculation results can provide data support for tunnel maintenance management units to make scientific decisions regarding tunnel maintenance.

Disclosure statement

The authors declare no conflict of interest.

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