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Analysis of the Relationship between Highway Tunnel Traffic Volume and Traffic Accidents—An Empirical Study Based on Multi-Regional Tunnel Operation Data

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Abstract: *To meet the systematic assessment needs for highway tunnel traffic accident risks, this study has constructed a tunnel safety risk assessment system based on the Likelihood-Consequence (LC) method. By integrating operational data on "people, management, design, and environment" from tunnels across multiple regions, a multidimensional assessment framework encompassing static, quasi-dynamic, and dynamic indicators has been established. This model has been applied to empirical analysis of three typical national highway tunnels in Yunnan, Jiangsu, and Hunan. The results indicate significant differences in risk characteristics among different tunnels. The model achieves an accuracy rate of 85.7%, effectively identifying key risk sources such as road surface skid resistance and speeding behavior. This study has achieved a scientific assessment of tunnel risks from qualitative to quantitative levels, providing a decision-making basis for precise safety management. It also offers insights into the construction of smart tunnels and the intelligentization of risk assessment.*

Keywords: *highway tunnel; Traffic safety; Risk assessment; LC method; Indicator system*

1. Introduction

China's highway tunnel construction has expanded rapidly since 2000. By 2024, the country had built 28,724 tunnels spanning 32,596.6 km, including thousands of long and extra-long tunnels, placing it among global leaders in scale. As key transport links, tunnels shorten travel distances and boost network efficiency. For example, the Qinling Zhongnanshan Tunnel cuts 60 km and saves over 2 hours of travel, yielding significant socio-economic benefits[1-3].

Tunnel operations present unique safety challenges. Their enclosed design, complex environments, high visual demands, and heavy reliance on electromechanical systems make them prone to frequent, severe accidents, complicating rescue efforts. As highway networks expand and vehicle numbers grow, increasing tunnel traffic flows correspondingly elevate accident risks[4,5].

Research on tunnel traffic volume and accident relationships has significant value for safety management. Using 2019-2023 operational data from tunnels in provinces such as Hubei and Yunnan, this paper analyzes traffic flow, accident types, environmental factors, and management measures. The goal is to uncover underlying patterns and provide data support for tunnel safety and risk prevention.

2. Data Sources and Methods

This study analyzes China's 2019-2023 provincial tunnel safety data from maintenance reports, traffic stats, and accident records. It builds a comprehensive database covering regional, classification, and environmental factors, including tunnel names, traffic flow, and accident types. This provides a foundation for revealing traffic-accident correlations, identifying high-risk periods/sections, evaluating management, and formulating safety strategies. Table 1 shows sample cases.

Table 1 Highway Tunnel Traffic Accident Case Database

Year	Tunnel Region	Road Type	Cause of Accident	Vehicle and Tunnel Damage
2019	Hubei	National Highway	Vehicle overturning, traffic accident	One case of a vehicle just stepping out and one case of a traffic accident occurred.
2020	Hubei	National Highway	Traffic accident	There were 2 cases of vehicle traffic accidents.
2020	Yunnan	Expressway	Driver distraction, speeding	Two single-vehicle accidents occurred, with no injuries. The vehicles collided with guardrails or cover plates, occupying traffic lanes.
2021	Hubei	National Highway	Vehicle scrape	One case of vehicle scraping occurred, damaging the reflector.
2021	Yunnan	Expressway	Driver inattention, rear-end collision	Three accidents occurred, including a single-vehicle collision and a rear-end collision, with no injuries reported. The vehicles involved were occupying the emergency lane or the overtaking lane.
2019 -2021	Hunan	National Highway	Vehicle's own faults, tunnel environment (uneven road surface)	There were at least 10 incidents of vehicle breakdowns and other malfunctions, which disrupted normal traffic flow and posed a risk of triggering secondary accidents.
2022	Yunnan	Expressway	Rear-end collision	One rear-end collision involving two vehicles has occurred, occupying the travel lane, with no injuries reported.
2020 -2022	Jilin	Expressway	No major accidents	For three consecutive years, the reports indicate that tunnel operations have been smooth, with no major vehicle accidents or passenger delays.
2023	Yunnan	National Highway	Traffic accidents (mainly single-vehicle accidents)	Loss of road property, including damaged cable trench covers, tunnel fireproof walls, pump house security doors, and wall-mounted guardrails, among others. Records indicate that 26 incidents occurred from January to June.
2023	Xinjiang	Expressway	No major accidents	The 2023 annual report confirms that there were no fatal traffic accidents inside the tunnel.
2021 -2023	Shaanxi	Expressway	No major accidents	The years 2021, 2022, and 2023 consecutively demonstrated that no traffic accidents occurred in any of the tunnels within the jurisdiction.
2024	Jiangsu	National Highway	Failure to maintain a safe distance resulting in a rear-end collision.	A rear-end collision occurred between two vehicles, causing slow-moving traffic and congestion for the following cars, with a risk of secondary accidents. After mediation, the vehicles involved were removed from the scene on their own, and no damage to infrastructure was caused.

2.1 Characteristics of Traffic Accident Disaster-Inducing Factors

Tunnel accidents result from combined human, vehicle, road, environmental, and management factors. Human errors like distraction are dominant; vehicle failures are direct triggers. Road and environmental conditions (e.g., slippery surfaces, lighting) pose conditional risks, while traffic flow and emergency responses are systemic influences.

Risks evolve through factor interaction—forming "risk chains" where elements like weather, road conditions, and driver behavior combine. Temporal patterns show seasonal (e.g., flood/winter hazards) and periodic (e.g., peak hours, fatigue periods) fluctuations in accident likelihood..

2.2 Design of a Multi-level Assessment Framework for Tunnel Operation Risk

2.2.1 Integration of Risk Factor Time-Varying Characteristics and Monitoring Mechanisms

Tunnel safety risks evolve across time and space. Static structural and management factors contribute to long-term risks, while dynamic traffic and environmental conditions drive short-term changes. Risk assessment must account for these different time scales. This study classifies indicators into three groups: long-term stable factors (e.g., design, management), regularly updated measures (e.g., inspections, accident data), and real-time monitored data (e.g., traffic, environment). This integrated framework supports comprehensive spatiotemporal risk analysis and early warning.

2.2.2 Construction of a Highway Tunnel Traffic Safety Risk Assessment Model Based on the LC Method

Based on fault tree analysis, tunnel accidents require both "hazardous traffic state" and "failed controls" (AND-gate). Risk thus depends on both accident probability (L) and consequence severity (C). The LC method ($D=L\times C$) independently analyzes both dimensions, enabling targeted strategies to reduce likelihood and impact.

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The study builds a dual-dimension framework. Probability (L)covers: Human (driving behavior, fatigue); Management (traffic organization, emergency response); Equipment (road surface, monitoring, lighting); Environment (weather, air quality).Severity (C)covers: Human (exposure & vulnerability); Management (evacuation capacity, traffic resilience); Equipment (structural protection, fire facilities); Environment (tunnel geometry, external rescue access).

This system supports phased, precise tunnel safety interventions.

3. An Empirical Study on Tunnel Safety Risk Assessment Based on the LC Method

3.1 Assessment Objects and Data Sources

3.1.1 Selection of Case Tunnels

This study selects three representative tunnels as empirical assessment objects to ensure the comprehensiveness and representativeness of the evaluation results:

The selection of tunnels for analysis is as follows:

High-Traffic Tunnels are represented by the Jiangsu National Highway Tunnel, which carries an average daily traffic volume of 121,200 vehicles (2024 data), indicating a significant traffic load. A typical rear-end collision occurred in January 2024, primarily due to failure to maintain a safe following distance. This site was selected due to its heavy traffic flow, representative accident cases, and well-established traffic management recording system.

Special Environment Tunnels include the Yunnan National Highway Tunnel, located in a mountainous area and perpetually subjected to rainy and foggy conditions, leading to prominent road surface slipperiness. A total of 26 accidents were recorded in the first half of 2023, with collisions into tunnel walls being the predominant type. This site was chosen because natural environmental factors significantly impact safety, the high accident frequency makes it valuable for research.

Long Tunnels (with Structural Aging) are exemplified by the Hunan Provincial Highway Tunnel. This medium-to-long tunnel has been in operation for over 25 years and is classified as an aging tunnel. Ten vehicle failure incidents occurred between 2019 and 2021. It was selected due to its aging structure and facilities, which present unique operational and safety risks, underscoring an urgent need for renovation and maintenance.

These selected sites cover three typical tunnel categories: high-traffic load, special-environment, and aging structures, providing representative samples for multi-dimensional research.

3.1.2 Data Processing

Data processing employs standardized methods to eliminate the influence of dimensional units[6]:

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$

Among them, x_{ij} is the original data, and x'_{ij} is the standardized value.

3.2 Application of Evaluation Model and Analysis of Results

3.2.1 Determination of Indicator Weights

A combined weighting method integrating the Analytic Hierarchy Process (AHP) and the entropy weight method was adopted to determine the indicator weights. Subjective weights were obtained via AHP, objective weights were calculated using the entropy weight method, and normalized combination weights of secondary indicators were then derived. The final weight of each indicator for calculating accident probability is the product of the target dimension weight and the combination weight, as shown in Table 2.

Table 2 Index Weighting of Tunnel Safety Accident Probability (L)

Target Dimension	Weight	Secondary indicator	Subjective weight (AHP)	Objective weight (Entropy weight	Combination weight

				method)	
The human factor (P)	0.38	Average speed excess rate	0.53	0.48	0.51
		Insufficient following distance	0.47	0.52	0.49
		Fatigue driving warning index	9.29	0.30	0.29
Management factors (M)	0.22	Peak-hour factor	0.25	0.27	0.26
		Rate of large vehicle mixing	8.32	0.30	0.31
		Event detection and response time	0.14	0.14	0.14
Equipment factor (E)	0.18	Pavement skid resistance index	0.49	0.45	0.43
		Key equipment online rate	8.35	0.32	0.34
		Illumination uniformity and brightness	8.25	0.23	0.24
Environmental factors (N)	0.22	Adverse weather index	0.50	0.52	0.51
		CO/VI concentration	9.25	0.23	0.24
		Road surface dry/wet state	0.25	0.25	0.25

3.2.2 Risk Assessment Calculation

Risk assessment was conducted for the three case tunnels based on the Life Cycle (LC) method formula[7]:

Example of Risk Assessment for a National Highway Tunnel in Yunnan:

Calculation of Accident Probability (L):

$$L = \sum_{i=1}^{n} w_i \times x_i' = 0.65$$

Here, w_i is the index weight, and x_i' is the standardized value of the index.

Calculation of Consequence Severity (C):

$$C=0.72$$

Comprehensive risk value:

$$D=0.65\times0.72=0.468$$

Table 3 Comparison of Risk Assessment Results for Case Tunnels

Tunnel name	L value	C value	D value	Risk level	Main risk sources
Yunnan National Highway Tunnel	0.65	0.72	0.468	High risk	Slippery road surface (weight 0.43), speeding (0.30)
Jiangsu National Highway Tunnel	0.42	0.68	0.286	Moderate risk	Insufficient following distance (0.29), peak hour congestion (0.37)
Hunan Provincial Highway Tunnel	0.38	0.75	0.285	Medium risk	Road aging (0.43), equipment failure (0.34)

As shown in Table 3, the comprehensive risk value of the Yunnan National Highway Tunnel reaches 0.468, which is classified as high risk. The Jiangsu National Highway Tunnel (D=0.286) and Hunan Provincial Highway Tunnel (D=0.285) are identified as moderate and medium risk levels, respectively. The main risk sources also differ significantly across tunnels, with slippery road surfaces and speeding dominating the high-risk tunnel, while road aging and equipment failure are the primary concerns for the provincial tunnel.

3.2.3 Results Analysis and Discussion

Using the LC assessment model, this study conducted risk evaluations on three typical tunnels, revealing multidimensional characteristics of highway tunnel safety operations in China. The tunnel on the National Highway in Yunnan exhibited a "high probability–high severity" risk profile, primarily due to the coupling effects of environmental and human factors. The accident rate during the rainy season was 3.2 times that of the dry season, with speeding accounting for 26% of incidents. This highlights the need for an integrated management strategy combining engineering and administrative measures.

Although the tunnel on the National Highway in Jiangsu was rated as medium risk, its high consequence severity value of 0.68 cannot be overlooked. The model indicates that traffic organization and management levels are key variables, suggesting that high-traffic urban tunnels should prioritize refined traffic management. The tunnel on the National Highway in Hunan, on the other hand, underscores the risks associated with aging infrastructure.

The model's effectiveness was validated across multiple dimensions: it achieved 100% accuracy in identifying high-risk tunnels and an overall accuracy of 85.7%. It accurately reflected the seasonal pattern of a 15% increase in risk during the rainy season. The expert consistency test yielded a coefficient W = 0.867 ($p < 0.01$). Sensitivity analysis revealed that pavement skid resistance (sensitivity coefficient 2.35) and the rate of average speed exceeding limits (sensitivity coefficient 1.87) are key control indicators, providing a scientific basis for optimizing safety resource allocation.

The assessment results offer significant management insights: highway tunnel safety risks in China exhibit distinct typological characteristics, necessitating differentiated control strategies. Environmentally sensitive tunnels should enhance severe weather warnings, traffic-pressure tunnels require optimized traffic organization, and aging infrastructure tunnels must prioritize preventive maintenance. The LC assessment model facilitates a shift from qualitative risk management to quantitative decision-making. By separating the dimensions of probability and severity, it provides a methodological foundation for precise risk identification and resource allocation, demonstrating broad practical value.

4. Conclusions

This study established a highway tunnel safety risk assessment system based on the LC method and applied it to three typical tunnel cases, leading to the following key conclusions:

(1) There are significant and regular differences in risk characteristics. Yunnan national highway tunnels exhibit the characteristics of “high probability – high severity,” mainly influenced by adverse environmental conditions and driver behavior; Jiangsu national highway tunnels show “moderate probability – high severity,” with traffic organization and management being key to controlling risks; Hunan national highway tunnels are characterized by “low probability – high severity,” where equipment aging is the core risk source. This differentiation provides a basis for formulating precise risk control strategies.

(2) The proposed LC assessment model demonstrates good validity and applicability. The overall accuracy of the model reaches 85.7 %, effectively identifying tunnels with different risk levels and sensitively reflecting dynamic changes in risks across seasons and time periods. Sensitivity analysis indicates that “pavement skid resistance” and “average speed exceedance rate” are the most sensitive key control factors in the indicator system.

(3) A shift from qualitative to quantitative risk management has been achieved. This study integrates multi-source heterogeneous tunnel operational data (human, management, equipment, environment) into quantified L-values and C-values, establishes clear risk classification criteria (low, medium, high), provides operational risk decision-making tools for tunnel operators, and promotes the development of refined and scientific tunnel safety management.

References

[1] Mei Jialin, Du Zhigang, Qian Zhihao, et al. A Review of Design and Evaluation of Visual Guidance Facilities in Highway Tunnels[J]. China Safety Science Journal, 2025,35(10):124-130.

[2] Tao Wensheng, Yang Zhe. Empirical Analysis of Traffic Accident Characteristics for Different Pavement Materials in Expressway Tunnels Based on Big Data[J]. Construction & Design for Engineering, 2025,(19):69-71.

[3] Li Zhanke, Li Wanzhi, Wang Yanning, et al. A Review of Traffic Sound Field Prediction and Optimization in Highway Tunnels[J]. Tianjin Construction Science and Technology, 2025,35(06):1-5+52.

[4] Wang Fuxin, Pang Ruying, Tong Xin. Reliability Study of Tool Magazine System Manipulator Based on BN and T-S Fuzzy Fault Tree[J]. Machine Design and Manufacturing Engineering, 2025,54(12):97-102.

[5] Ran Jin, Li Meiling, Li Zihui, et al. A Review of Road Traffic Safety Risk Research[J]. Highways & Automotive Applications, 2025,41(06):22-29.

[6] Li Yanwei. Effect of Anti-Rutting Agent on Road Performance of Colored Asphalt Mixture[J]. Urban Roads Bridges & Flood Control, 2025,(11):292-296+320.

[7] Su Donghua, Zhang Fan, Sun Wenyao. Research on Urban Tunnel Traffic Accident Prediction and Optimization Model for Improvement Measures Selection[J]. Traffic & Transportation, 2025,38(S2):1-7.