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Development of a Multi-Criteria Indicator System for Safe Site Selection of Long Mountain Tunnels in Highway Projects

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Abstract

The construction of long and large-scale mountain tunnels represents a pivotal component in highway infrastructure, where site selection plays a decisive role in ensuring both construction safety and long-term operational stability. Nonetheless, factors such as intricate geological conditions, environmentally sensitive terrains, and fluctuating economic contexts introduce considerable uncertainty into the decision-making process. To tackle these complexities, this study proposes a structured multi-criteria evaluation framework by establishing a targeted indicator system for tunnel siting in mountainous regions. The system incorporates a balanced set of criteria encompassing social, economic, environmental, and technical safety aspects, aiming to reflect the multifaceted nature of siting risks comprehensively. By formulating this index-based decision support tool, the research enables a more transparent and rational assessment of alternative locations. The framework not only facilitates improved decision reliability under uncertainty but also contributes to enhancing risk management practices in complex terrain infrastructure planning.

Keywords

Multi-Dimensional; Large-scale mountain tunnels; Site selection; Safety decision indicators.

1. Introduction

Tunnel alignment planning is typically carried out after the main transportation corridor has been determined. It involves a comprehensive assessment of geological conditions, construction safety, and economic feasibility to define the tunnel's spatial location, depth, and alignment. In western China's mountainous regions, the geological environment is notably complex, often featuring unfavorable conditions such as high in-situ stress, permafrost, water-rich strata, and karst formations. These areas are also prone to frequent geological hazards, posing significant threats to project safety. As key control structures in transportation networks, tunnel locations directly influence the overall route layout and traffic reliability. To achieve safe and sustainable siting, it is essential to balance engineering cost and environmental conservation. Therefore, there is an urgent need to develop a multidimensional risk assessment and decision-making model tailored to the challenges of complex mountainous terrains.

In recent years, the technical system for planning mountain transportation tunnels has become increasingly refined, with scholars conducting extensive studies from multiple perspectives, including disaster mitigation, route optimization, geological assessment, and digital integration.

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In the domain of hazard analysis, Li et al. conducted a comprehensive study on engineering site selection in the Himalayas, addressing five key aspects: regional geological evolution, fault activity, stress field characteristics, disaster chain mechanisms, and siting methodologies[1]. Bin et al. developed a critical path model that incorporates tunnel siting, excavation processes, and ecological impacts[2]. Focusing on the Sichuan–Tibet Highway, Zou et al. introduced an integrated vulnerability assessment model for debris flow hazards, enabling quantitative evaluation of risks in mountainous road systems[3]. Similarly, Hu et al. investigated the spatial distribution and dynamics of debris flows along the Bomi–Ranwu section of the Sichuan–Tibet Railway, identifying dominant controlling factors to inform alignment decisions[4].

In terms of route optimization in complex mountainous terrain, Chuanqi et al. employed a hybrid approach combining AHP, fuzzy comprehensive evaluation, and cloud modeling to determine the optimal alignment scheme for the Qiongzhou Strait subsea tunnel[5]. Qu et al. proposed a dynamic weighting interaction matrix model to enhance the scientific robustness of railway alignment decisions[6]. Wan et al. introduced a three-stage optimization strategy that simultaneously considers construction cost, structural stability, and route consistency[7].

For geological evaluation, Shi et al. utilized Sentinel-1 satellite data to assess the stability of highways in cold regions, offering new insights for route planning in periglacial environments[8]. Zhang et al. established a 3D geomechanical model incorporating fault zones, enabling accurate back-analysis of in-situ stress fields in deep-buried tunnels[9].

In the field of information-based planning, Liang et al. demonstrated the integration of geological mapping and BIM technologies in tunnel scheme comparison for the Winter Olympics infrastructure[10]. Xue et al. drawing on the NTI database, developed a TOPSIS-CRITIC evaluation framework that significantly improved the objectivity and comprehensiveness of tunnel condition assessments[11].

Significant progress has been made in recent years in the study of mountain tunnel siting, particularly in areas such as disaster prevention, route optimization, geological analysis, and digital technology integration. These efforts have contributed to the development of a relatively comprehensive technical framework. However, under complex geological conditions, there remains a notable gap in the availability of a systematic and risk-oriented evaluation index system. This study addresses that gap by focusing on long tunnel projects in western mountainous regions, proposing a multidimensional safety decision-making indicator framework aimed at providing a standardized and scientifically grounded basis for tunnel site selection.

2. Tunnel Planning Safety Decision Uncertainty Analysis

Site selection planning plays a critical role in tunnel safety decision-making. The quality of such decisions not only affects the safety and feasibility of construction but also has long-term implications for operational reliability and maintenance security. In the context of mountainous transportation tunnels, uncertainties in siting safety decisions primarily arise from two key aspects. First, there is uncertainty in the decision content—specifically, whether the selected indicators sufficiently capture the core factors influencing safety, and how interdependencies among these indicators may obscure clear evaluation. Second, methodological uncertainty exists due to the nature of the information provided by decision-makers, which is often vague, hesitant, or preference-driven. Furthermore, subjective judgments in the planning process can exacerbate this uncertainty, leading to inconsistencies in safety assessments.

The safety-oriented decision-making process for tunnel siting must account for both macro-level influencing factors and the specific characteristics of individual engineering projects. Table 1 presents a summary of current research on decision-making indicators used in route alignment and tunnel planning.

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Table 1. Summary of Research on Decision-Making Indicators for Route Alignment Planning

No.	Authors	Planning Type	Indicator Level
1	Zou Qiang et al., 2018[3]	Mountain Highway	Environmental sensitivity Structural characteristics Functional role, Exposure probability, Number of affected entities
2	Hu Guisheng et al., 2019[4]	Mountain Railway	Characteristic Factors, Dominant (or Controlling) Factors, Mitigation Model
3	Xinjie Wan, et al., 2025[7]	Tunnel	Construction Cost, Structural Stability, Route Continuity
4	Xuguo Shi et al., 2022[8]	Permafrost Region Highway	Seasonal Displacement, Time Lag, Linear Deformation Rate
5	Zhiqiang Zhang et al., 2021[9]	Extra-Long Tunnel	Fault fracture zone, Water inflow, Surrounding rock stability
6	Yang Liang-quan et al., 2020[10]	Tunnel	Ground stress distribution, Horizontal stress, Fault effect
7	Xue Ya-Dong, et al., 2024[11]	Tunnel	Structural, Transportation and Civil Works, Non-Structural
8	Dalia Said, et al., 2024[12]	Mountain Highway	Safety Factors, Hydrological Factors, Geological Factors
9	Svetla Stoilova, et al., 2024[13]	Transportation Route	Environment, Technology, Infrastructure, Economy, Safety
10	Rens Kamphuis et al., 2025[14]	Road	Travel time mean, Travel time variance, Travel time uncertainty

According to the statistical results in the above table, macro-level factors influencing route selection and planning decisions cannot be considered in isolation from political, economic, social, cultural, and natural environmental aspects. At the micro level, the influencing factors can be primarily summarized as project cost and technology.

3. Decision Index System

Since the tunnel site selection and planning phase represents the preliminary stage of project implementation, where detailed decision-making parameters are not yet available, the decision-making process should prioritize macro-level considerations while supplementing with micro-level factors.

3.1. Social safety

Social safety refers to the impact of tunnel site selection and planning on social stability risks. Its safety risk scope involves stakeholders with vested interests from the project starting point to areas along the route. The social safety of tunnel planning and site selection can be considered from three aspects: direct input impact, output impact, and potential impact.

The direct input impact refers to direct economic investment during construction. Considering that mountain residents may affect tunnel construction safety to some extent, population relocation is taken as the direct input impact for long mountain tunnels.

The output impact refers to the effects achieved after tunnel completion. Reasonable route selection can meet the safety requirements during operation and maintenance of long mountain tunnels by improving traffic flow and optimizing traffic network layout.

The potential impact refers to potential benefits that can be obtained. Appropriate route selection needs to meet local demands, drive regional economic development along the route, and thereby generate social stability and safety benefits.

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Therefore, this paper considers factors including relocation area, traffic flow improvement, traffic network optimization, and fulfillment of local needs.

3.2. Economic safety

Economic safety means that tunnel planning decisions will directly affect the construction cost and implementation plan, thereby influencing the construction and operational safety of the tunnel. The economic indicators in engineering are reflected in preliminary project investment, later operation and maintenance costs, and transportation revenue.

With reference to engineering economic indicators, this study classifies the economic indicators of long mountain tunnels into three categories: initial investment, later investment, and investment benefits. Initial investment mainly refers to the total project investment cost. Later investment primarily includes operation and maintenance expenses. Investment benefit indicators are reflected in the economic internal rate of return.

Therefore, this paper mainly considers the impacts of total project investment cost, operation and maintenance expenses, and economic internal rate of return.

3.3. Environmental impacts

The environmental impacts of tunnel construction are manifested in its effects on water resources, forest vegetation, wildlife, and farmland soil. Based on different affected subjects, the environment can be divided into natural environment and living environment.

The natural environment includes water resources, soil, flora and fauna, and other ecological systems. The living environment refers to human activity environments in the region, including farmland, forestry, and other agricultural/forestry ecosystems.

Long mountain tunnels are characterized by their large scale and extensive land use, inevitably causing some degree of impact on sensitive ecosystems during construction. Meanwhile, the environment also affects the construction and operational safety of these tunnels.

Therefore, this study primarily considers the impacts on both natural ecological environments and agricultural/forestry ecological environments.

3.4. Technical Safety

Technical Safety focuses on assessing construction difficulty and operational maintenance challenges, which are crucial for ensuring tunnel safety. For long mountain tunnels, this study classifies technical indicators into two categories: project scale and construction difficulty.

Project scale is characterized by: Total tunnel length, Maximum burial depth. Construction difficulty considers Surrounding rock classification, Adverse geological conditions. These engineering factors critically impact both construction safety and long-term operational security. By systematically evaluating these aspects, optimal solutions can be selected.

This study employs three key decision-making indicators: Total tunnel length, Maximum burial depth, Engineering geological conditions.

3.5. Decision index system

The safety decision-making framework for mountain long-distance traffic tunnel site selection is structured around four criterion layers: social safety, economic safety, environmental safety, and technical safety. Macro-level considerations encompass social safety, economic safety, and environmental safety. Micro-level considerations focus primarily on technical safety as the key influencing factor. The established safety decision-making index system for mountain long-distance traffic tunnel site selection is illustrated in Figure 1.

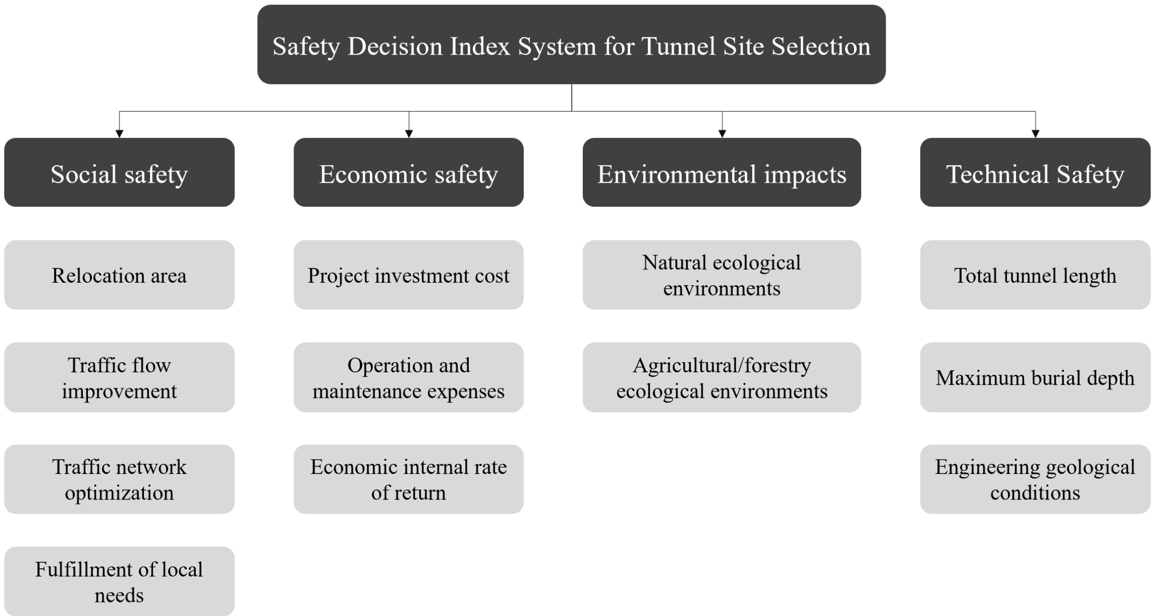

Figure 1. Safety Decision-Making Index System for Site Selection and Planning of Long Mountain Traffic Tunnels

4. Conclusion

Focusing on the safety-oriented site selection of long traffic tunnels in the geologically complex and high-risk mountainous regions of western China, this study establishes a multi-criteria safety evaluation index system. Using principal component analysis to determine objective weights for each indicator, we developed a scientific comprehensive assessment framework.

The research constructs a multidimensional index system for mountain tunnel site selection, systematically covering four key aspects: social, economic, environmental and technical safety. This system comprehensively reflects critical risk factors in the site selection process, demonstrating good applicability and extensibility.

The findings provide decision-making support for planning transportation infrastructure in complex mountainous areas, offering significant practical value for enhancing both safety standards and investment efficiency in long mountain tunnel projects.

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