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# Advancing Tunnel Safety Management: A Simple and Adaptable Method for Comprehensive Evaluation

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**Abstract:**

Tunnel safety presents unique challenges, requiring a practical and adaptable evaluation method. To address this need, a comprehensive safety index was developed in this study. The Analytic Hierarchy Process (AHP) was used with a panel of 43 experts to assign evidence-based weights to seven key safety categories. The results show that 'Traffic Management and Surveillance' (24%), 'Emergency and Rescue Management' (21%), and 'Tunnel and Road Geometry' (19%) are the most critical factors. The model was then validated through a case study of the Shohada-ye-Gaza Tunnel in Tehran, which scored 5.85, corresponding to a "Mean" safety level. Specific weaknesses were successfully pinpointed by the evaluation, demonstrating its utility as a diagnostic tool. Furthermore, it was confirmed by a sensitivity analysis that a 30% improvement in the 'Traffic management and traffic surveillance' category would raise the tunnel's classification to "Good." This research provides a validated, straightforward framework that enables authorities to not only benchmark tunnel safety but also strategically allocate resources for targeted improvements.



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## 1. Introduction

Tunnel safety is critically important because tunnels present unique risks that differ significantly from those on open roads. The confined space, limited ventilation, and restricted access in tunnels can cause accidents to escalate quickly, often resulting in severe consequences such as fires, toxic smoke exposure, and structural damage that complicate rescue efforts and prolong closures [1].

The rapid expansion of highway tunnels and increasing traffic volumes have heightened the importance of improving tunnel safety. The severe consequences of tunnel accidents, such as the 1999 Mont Blanc Tunnel fire in France, which resulted in 39 fatalities, a three-year closure, and an estimated €392 million in economic losses, underscore the urgency of proactive safety measures. These losses encompassed reconstruction costs, operational disruptions, and long-term economic impacts, demonstrating the irreversible damage caused by tunnel disasters. This case highlights the necessity of integrating advanced risk assessment and mitigation strategies into tunnel infrastructure management [2].

As vital infrastructure for transportation systems and regional economies, highway tunnels operate in complex environments that expose them to combined stresses from construction quality, environmental conditions, and human factors-all of which threaten structural safety. At the same time, global tunnel networks are expanding rapidly [3].

When existing studies are examined, tunnel safety is generally addressed from two perspectives: First, accident prevention, with factors such as tunnel design, optimal traffic regulations, lighting standards, and maintenance protocols examined. Second, accident management is studied during incidents, including investigations of emergency exits, fire suppression systems, and the structural resilience of tunnels under extreme heat. This two-pronged approach is logical because tunnels are confined spaces, and both proactive accident mitigation and effective emergency response are required [4].

The unprecedented scale of tunnel infrastructure demands scientifically rigorous safety evaluation methods. As a result, developing advanced methodologies for highway tunnel safety has become a top research priority



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## 2. Literature Review

Safety evaluation in road tunnels is a critical research focus due to the potentially severe consequences of structural failures or operational hazards. Over the years, researchers and engineers have developed a wide range of methodologies to assess tunnel safety, each addressing distinct risk factors, including structural integrity, fire hazards, ventilation efficiency, and human evacuation performance. These methods vary in complexity, from qualitative risk matrices to advanced computational models that incorporate real-time monitoring data [5].

To further explore this topic, this section briefly discusses the methods currently available for assessing and monitoring tunnel safety.

### 2.1. Existing Methods of Safety Evaluation in the Road Tunnels

According to the PIARC[1] Quantitative Risk Assessment Model (QRAM) User's Guide: Quantitative Risk Analysis (QRA) for tunnel safety is a systematic method for quantifying risks associated with transporting dangerous goods through tunnels. The method involves selecting a limited set of relevant accident scenarios involving specific dangerous goods and simultaneously evaluating their probabilities of occurrence and consequences. This enables the quantitative assessment of societal risk and individual risk, specifically for tunnel sections or routes. The model supports the comparison of societal risks against reference criteria and supports decision-making regarding tunnel safety requirements within regulatory frameworks. The QRA model is complex, requires substantial input data, and is intended as a decision-support tool to supplement expert judgment in tunnel risk management [6].

Quantitative Risk Analysis (QRA) remains a cornerstone methodology for tunnel safety evaluation, particularly for assessing low-probability, high-consequence events such as fires or structural collapses. Modern QRA frameworks integrate probabilistic models with scenario-based analyses to quantify risks across tunnel design, traffic dynamics, and emergency systems. For instance, societal risk indices-expressed as F/N curves correlating incident frequency (F) and fatality numbers (N)-are widely adopted to benchmark safety against regulatory thresholds. These models account for variables such as traffic volume, hazardous material transport, and evacuation infrastructure, enabling authorities to prioritize mitigation measures, such as ventilation upgrades or emergency exit spacing. However, traditional QRA faces limitations in addressing non-uniform tunnel geometries and evolving operational conditions, prompting adaptations like the QRAFT model for heterogeneous urban tunnels [7].

Structural Health Monitoring (SHM) systems have emerged as critical tools for real-time safety evaluation, leveraging embedded sensors and fiber-optic technologies to detect deviations from design performance. These systems provide continuous data on parameters such as lining deformation, moisture ingress, and vibration patterns, enabling predictive maintenance and early warning of potential failures. Advanced SHM platforms integrate corrosion sensors, strain gauges, and third-party transducers into unified dashboards, facilitating lifecycle management from construction to decommissioning. While effective for physical infrastructure assessment, SHM's scope often excludes human behavioral factors and transient operational risks, which necessitate complementary evaluation approaches [8].

Hybrid Risk Assessment Models address the complexity of modern tunnels by merging data-driven techniques with traditional engineering analyses. The fuzzy Bayesian network (FBN) method exemplifies this trend, combining principal component analysis (PCA) to identify critical risk indicators, such as gas concentrations or geological instability, with probabilistic networks to quantify accident likelihood. Similarly, the Analytic Hierarchy Process (AHP), when paired with machine-learning-based anomaly detection, enables dynamic evaluation of worker safety by analyzing physiological data (e.g., heart rate, body temperature) alongside environmental metrics such as CO levels. These hybrid approaches overcome the limitations of static risk assessment but require extensive calibration datasets and computational resources, thereby limiting their scalability [9].

Digital Twin and Ensemble Learning Technologies represent the state of the art in tunnel safety evaluation, enabling virtual replicas that simulate real-world performance across diverse scenarios. By integrating IoT sensor data with computational fluid dynamics (CFD) and finite element modeling, digital twins predict fire spread patterns, structural stress points, and evacuation bottlenecks. Concurrently, ensemble learning models aggregate predictions from multiple machine learning algorithms to enhance anomaly detection accuracy, achieving superior performance in identifying hazardous worker states compared to single-model systems. While promising, these methods demand robust cybersecurity protocols and interdisciplinary expertise to implement effectively, which highlights the need for standardized validation frameworks [10].

Current tunnel safety assessment methodologies exhibit significant diversity, ranging from probability-based risk models to real-time structural monitoring via sensor networks, and include emerging approaches that integrate artificial intelligence and digital twin simulations. While these methods have advanced risk quantification through dynamic data integration and scenario modeling, persistent limitations remain, particularly in accounting for human behavioral factors, adapting to complex tunnel geometries, and achieving scalable validation. These gaps underscore the need for evaluation systems that balance technical rigor with operational practicality.

[1] Permanent International Association of Road Congresses

Many countries classify tunnels based on their conditions and risk potential. The greater the risk potential (e.g., incident frequency and the severity of potential consequences), the higher the grade assigned to the tunnel. Conversely, a higher-grade tunnel requires more extensive and cautious safety measures. Consequently, the quantity and characteristics of equipment and facilities necessary to ensure safety are determined according to each tunnel's grade. Therefore, grading plays a crucial role in establishing safety standards across various tunnel components. Among these components, the length of the tunnel and the characteristics of traffic are the most significant [11].

Table 1 shows the classification of tunnels according to the standards of the European Commission [12]:

**Table 1. Tunnel Classification [12]**

| Traffic Volume (veh/lane/day) | Tunnel Length (m) | Tunnel Classification |
|---|---|---|
| ≥ 2000 | >3000 | 1 |
| ≥ 2000 | 1000 ≤, ≤ 3000 | 2 |
| ≥ 2000 | 500≤ , ≤ 1000 | 3 |
| < 2000 | L >1000 | 4 |
| < 2000 | 500≤ , ≤ 1000 | 5 |

The foundational work has established a systematic classification of tunnel safety factors into seven key categories based on operational and systemic properties [13].

• Tunnel and road geometry (e.g., alignment, cross-section design)

• Traffic management and surveillance (e.g., speed control, incident detection)

• Emergency and rescue systems (e.g., evacuation routes, response protocols)

• Fire resistance and protection (e.g., fireproof materials, suppression systems)

• Communication systems (e.g., emergency broadcasts, sensor networks)

• Ventilation systems (e.g., smoke control, airflow dynamics)

• Lighting and power supply (e.g., backup electricity, luminance standards)

Each category encompasses specific sub-factors that collectively determine overall safety performance, as detailed in the original framework [13].

### 2.2. AHP Applications in Tunnel Engineering and Safety Assessment

The Analytic Hierarchy Process (AHP) is a well-established multi-criteria decision-making (MCDM) tool valued for its ability to structure complex problems and systematically incorporate expert judgment. Its application in civil and mining engineering is widespread, particularly for problems involving multiple conflicting criteria.

In the context of tunneling, AHP has been successfully applied to specific, bounded engineering decisions. For example, Oraee et al. developed an AHP model to select the optimal tunnel support system for a coal mine in Iran [14]. Their model's goal was to choose a support design (e.g., specific combinations of steel sets and rock bolts) by comparing a pre-selected set of technically viable options. The decision criteria were heavily focused on geomechanical performance (e.g., vertical and horizontal displacement) and direct economic factors (e.g., support system cost) [14]. While this demonstrates the utility of AHP for a specific design-phase decision, its scope is limited to structural engineering. It does not extend to the tunnel's holistic operational safety post-construction.

More recently, AHP has been used for broader risk assessment during the construction phase. Pyakurel and Adhikari utilized AHP to identify and rank risks associated with tunnel construction in the challenging geology of the Nepal Himalaya [15]. Their hierarchy identified major risk areas, with "Geo-technical" risks emerging as the most significant factor, followed by natural hazards and safety-related risks during construction [15]. This model is valuable for project managers during the planning and construction phases, helping to anticipate and mitigate potential hazards like rock mass collapse, water inrush, and worker safety issues. However, its primary focus is on pre-completion and construction-phase risks rather than the long-term operational safety of a completed, active tunnel.

While these studies validate the use of AHP in tunnel engineering, they also highlight a clear gap that the present study aims to fill. Previous models have been tailored for either (a) discrete engineering design choices [14] or (b) construction-phase risk management [15]. A framework for the holistic, ongoing operational safety assessment of active highway tunnels remains underdeveloped. The model proposed in this paper advances the application of AHP by:

Shifting the Focus to Operational Safety: Our model evaluates the in-service safety of completed tunnels by incorporating a broader range of criteria beyond geomechanics, including emergency management, operational procedures, and human factors.

Introducing a Risk-Based Penalty Mechanism: A key novelty of our approach is the integration of a Safety Factor (S.F.), which adjusts the final score based on the tunnel's inherent risk profile (e.g., traffic volume, transport of hazardous goods). This provides a more conservative and realistic safety evaluation, which is absent in the direct AHP output of the aforementioned studies.

Designing for Portfolio Management: Unlike case-specific models, our framework is a standardized tool for transport authorities to systematically evaluate and compare safety levels across a network of diverse tunnels, enabling prioritized resource allocation for maintenance and upgrades.

### 2.3. Conceptual Framework and Research Gap

To synthesize the diverse methodologies discussed above, existing tunnel safety evaluation approaches can be broadly categorized into four conceptual groups:

1. Probabilistic risk models such as QRA, which quantify accident likelihood and consequences;

2. Real-time structural monitoring systems like SHM, which focus on physical infrastructure performance;

3. Hybrid models that integrate statistical and expert-based techniques, including fuzzy Bayesian networks and AHP;

4. Emerging technologies such as digital twins and ensemble learning, which simulate tunnel behaviour under dynamic conditions.

While each group contributes valuable insights, limitations persist—QRA models often require extensive data and struggle with non-uniform tunnel geometries; SHM systems exclude human factors; hybrid models demand high computational resources; and emerging technologies face implementation barriers due to cybersecurity and interdisciplinary complexity. These gaps highlight the need for a simplified, expert-driven evaluation framework that balances methodological rigor with practical applicability. The model proposed in this study aims to fill this gap by combining AHP with a weighted scoring system, enabling transparent, adaptable, and resource-efficient safety assessment across diverse tunnel environments.

## 3. Methodology

This study employs a combined qualitative and quantitative approach, adopted due to the common scarcity and limitations of recorded data on road tunnel safety. The methodology is based on two key steps:

• Assigning a weight to each factor affecting tunnel safety

• Establishing a linear relationship between these factors and the resulting safety index

The overall tunnel safety value is calculated by aggregating the operational quality of all relevant factors. Because each factor has distinct properties, tunnel safety is treated as a function of multiple variables. Consequently, the more optimally these variables perform, the higher the resulting level of tunnel safety.

This study's methodology is centered on a linear aggregation model, which provides a straightforward and practical framework for integrating multiple safety-influencing variables. Overall tunnel safety is conceptualized as the weighted arithmetic mean of the performance quality of its constituent factors. This approach allows for the calculation of a quantitative Tunnel Safety (TS) index.

The TS index is formulated as the sum of the products of each factor's score and its corresponding weight, as shown in Equation 1;

$$\mathrm{TS} = \sum_{i=1}^{n}(W_i \times S_i) \qquad (1)$$

where n represents the total number of primary safety factors considered, $S_i$ denotes the performance score of the i-th factor, evaluated on a cardinal scale from 0 (lowest safety performance) to 10 (highest safety performance), $W_i$ is the normalized weight assigned to the i-th factor, signifying its relative importance to overall safety.

The weighting system is constrained such that the sum of all primary factor weights is unity ($\Sigma W_i = 1$).

As depicted in the hierarchical structure in Figure 1, the overall safety is a function of parameters $T_1, T_2, T_3 ... T_n$. This framework is recursive; a primary parameter can be disaggregated into its own set of sub-groups. For example, if parameter $T_n$ comprises m sub-group ($T_{n1}, T_{n2}, ..., T_{nm}$), a set of local weights ($W_{n1}, W_{n2}, ..., W_{nm}$) is assigned. These local weights are also normalized to sum to one, ensuring coherence within the model ($\sum_{j=1}^{m} W_{nj} = 1$)

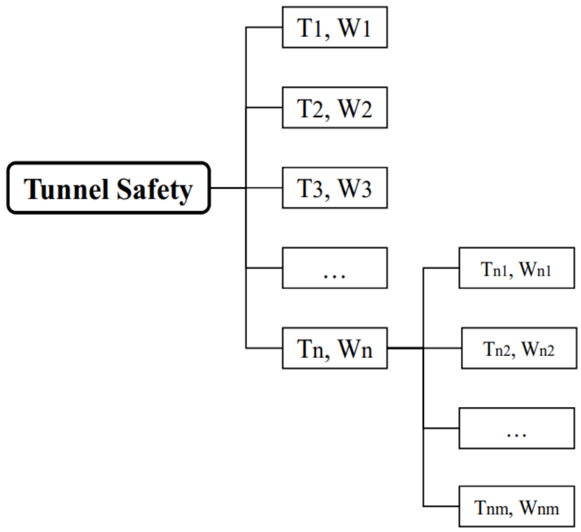


**Figure 1. Tunnel safety with respect to the affecting factors and their weighting**

### 3.1. Assessment Protocol and Implementation

The safety assessment methodology is implemented through a structured, multi-stage protocol. This process begins with the development of evaluation instruments, followed by expert-led data collection and parameter estimation.

#### 3.1.1. Component Scoring Procedure

An exhaustive inspection checklist is first formulated, enumerating all components and systems integral to tunnel safety. The core of the assessment is a scoring procedure conducted by a panel of vetted experts possessing deep expertise in tunnel engineering and familiarity with national safety regulations.

The panel evaluates the operational condition of each component and assigns a performance score ($S_{ij}$) on a cardinal scale from 0 to 10. A defined rubric governs this scoring:

• Score Assignment: The primary basis for scoring is a set of pre-established, quantitative guidelines. When objective metrics are unavailable, scores are determined by expert consensus.

• Scale Definition: A score of 0 denotes a critically deficient component (i.e., absent or entirely inoperative), while a score of 10 represents optimal, design-level performance.

• Intermediate Conditions: Scores between these extremes correspond to varying degrees of operational effectiveness, as delineated in Table 2. This structured approach aims to maximize measurement precision and minimize subjectivity.

**Table 2.** **Scoring guidelines based on operational conditions**

| Score Range | Condition |
|---|---|
| $8 < S \leq 10$ | Perfect |
| $6 < S \leq 8$ | Good |
| $4 < S \leq 6$ | Mean |
| $2 < S \leq 4$ | Weak |
| $0 \leq S \leq 2$ | Very bad |

#### 3.1.2. Derivation of Factor Weight

Concurrently, the relative importance of each safety factor is quantified by assigning weights ($W_i$ and $W_{ij}$). These weights are not derived from the performance scores but are established independently through a formal multi-criteria decision-making (MCDM) technique, such as the Analytic Hierarchy Process (AHP). This ensures that the weights reflect the intrinsic contribution of each factor to overall safety, as determined by expert consensus.

### 3.2. Calculation of the Final Safety Index

The methodological framework culminates in the synthesis of the granular, component-level scores into a holistic Tunnel Safety index. This quantitative aggregation is a two-stage process. First, a base safety score is computed using a hierarchical weighting model. Second, this base score is adjusted by applying a Safety Factor (S.F.) to account for the tunnel's inherent risk classification.

#### 3.2.1. Aggregation of the Base Safety Score

The base Tunnel Safety (TS) index is calculated by aggregating the weighted scores of all components and sub-components in the hierarchical model. The index is formulated as a nested weighted sum, as shown in Equation 2:

$$TS = \sum_{i=1}^{n} (W_i \times \sum_{j=1}^{m} (W_{ij} \times S_{ij})) \tag{2}$$

where TS is The base tunnel safety score, on a 0-10 scale,

n is The total number of primary safety factor, $m_i$ is The number of sub-factors within the i-th primary group, Wi is The normalized importance weight of the i-th primary factor group, Wij is The normalized local weight of the j-th sub-factor within the i-th group, Sij is the expert-assigned performance score (0-10) for the i-th group's sub-factor.

#### 3.2.2. Adjustment for Inherent Risk Classification

The inherent risk associated with a tunnel is strongly correlated with its physical and operational characteristics, such as length, traffic volume, and two-way traffic flow. To create a standardized measure of safety, a Safety Factor (S.F.) is applied to adjust the base TS score. This factor is always less than or equal to 1 and decreases for tunnels classified as higher risk.

The rationale for this adjustment is to enforce a more rigorous performance standard on higher-risk infrastructure. By penalizing their base score, the model ensures that a high-risk tunnel must exhibit a superior level of operational quality (i.e., achieve a higher base TS score) to attain a final safety rating comparable to that of a low-risk tunnel.

The Final Tunnel Safety Index ($TS_{final}$) is thus computed as the product of the base score and the corresponding safety factor, as per Equation 3:

$$\text{Final Tunnel Safety } (TS_{final}) = TS \times S.F. \tag{3}$$

The S.F. values for each pre-defined tunnel class, adapted from the literature are provided in Table 3 [13]:

**Table 3.** **Safety Factors Based on Tunnel Classification**

| Tunnel Classification | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Safety Factor | 0.86 | 0.89 | 0.92 | 0.96 | 1 |

### 3.3. Analytic Hierarchy Process (AHP)

The model proposed in this study requires a robust, objective method for determining the relative importance (weight) of each of the seven main safety categories. To achieve this, the Analytic Hierarchy Process (AHP), a structured multi-criteria decision-making (MCDM) technique developed by Saaty (1980), was employed. AHP is exceptionally well-suited to this problem because it enables the quantification of expert judgments, decomposes a complex decision into a manageable hierarchy, and systematically assesses the consistency of those judgments. The application of AHP for weight determination followed a rigorous, multi-step procedure:

1. Structuring the Decision Hierarchy: The problem was first decomposed into a two-level hierarchy, as illustrated in Figure 2. The overall goal, "Comprehensive Tunnel Safety," was placed at the top level. The second level comprised seven primary safety factors identified in the literature: Tunnel and Road Geometry, Lighting and Power Supply, Ventilation Systems, Traffic Management and Surveillance, Fire Protection, Communication Systems, and Emergency and Rescue Management.

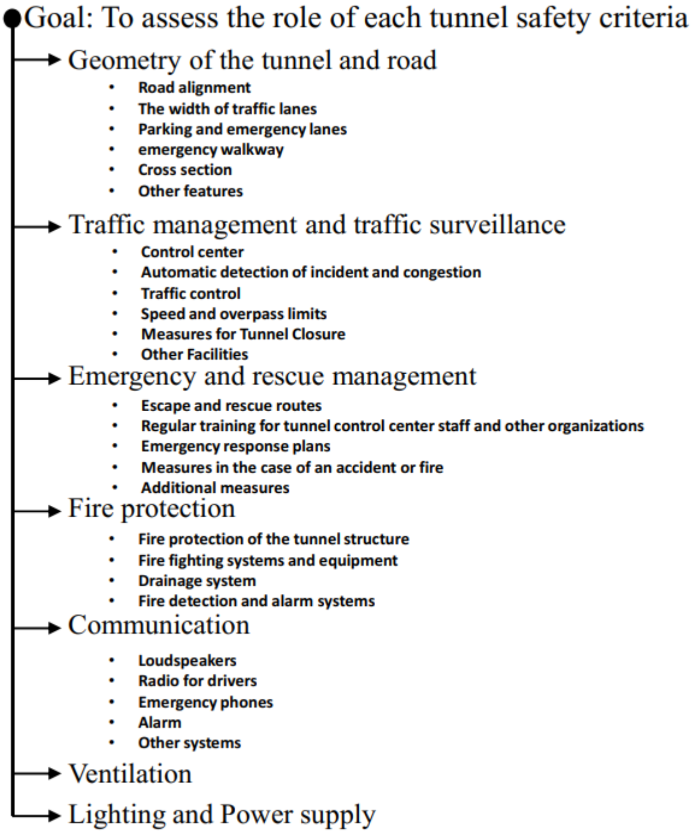


**Figure 2. Hierarchical Tree for the Tunnel Safety Model**

2. Expert Panel and Pairwise Comparisons: The panel consisted of 43 experts, a sample size that is exceptionally robust for an AHP-based study and significantly exceeds the commonly accepted range of 10–15 experts often cited in decision-making literature [16]. The statistical power of this large sample ensures a high degree of stability in the aggregated judgments, minimizing the impact of individual biases and enhancing the reliability of the final weights derived through the geometric mean [17]. Furthermore, the panel was deliberately stratified to capture a comprehensive spectrum of professional expertise, comprising 12 university professors, 15 Ph.D. candidates specializing in transport safety, 8 experts from the Ministry of Roads and Urban Development, and 8 experts from the Municipality of Tehran. This diverse composition ensures that the model reflects a balanced synthesis of academic, policy, and practical operational perspectives, thereby strengthening the generalizability of the resulting tunnel safety evaluation framework.

Each expert was provided with a questionnaire designed to facilitate the pairwise comparison of the seven main safety categories. Using Saaty's fundamental 1-to-9 scale (see Table 4), experts were asked to judge the relative importance of one criterion over another with respect to its contribution to overall tunnel safety (e.g., "How much more important is 'Traffic Management' than 'Ventilation Systems'?"). This process yielded 21 distinct comparative judgments from each of the 43 participants, forming the raw data for the AHP analysis.

**Table 4. Saaty's 9-Point Scale for Pairwise Comparison [18]**

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal Importance | Two factors contribute equally to the objective. |
| 3 | Moderate Importance | Experience and judgment slightly favour one factor over another. |
| 5 | Strong Importance | Experience and judgment strongly favour one factor over another. |
| 7 | Very Strong Importance | A factor is favoured very strongly over another; its dominance is demonstrated in practice. |
| 9 | Extreme Importance | The evidence favouring one factor over another is of the highest possible order of affirmation. |
| 2,4,6,8 | Intermediate Values | Used to represent a compromise between two judgments. |

3. Aggregation of Judgments and Consistency Check: Given that the data was collected from a panel of 43 experts, their individual judgments first needed to be synthesized into a single, collective viewpoint. This was accomplished by statistically aggregating their responses to produce a single consolidated comparison matrix that represents the group's consensus. This standard AHP practice ensures that no single expert skews the final priorities and that they

reflect the shared wisdom of the entire panel. A key strength of the AHP method is its built-in capability to check for logical contradictions in the experts' judgments. For example, if an expert rated Fire Protection as more important than Ventilation, and Ventilation as more important than Lighting, then logically, Fire Protection must also be rated as more important than Lighting. The process includes a formal check, known as the Consistency Ratio (CR), to measure the degree of such logical consistency across all judgments in the aggregated matrix.

The established threshold for acceptable consistency in AHP studies is a CR value of 0.10 or less. Our analysis confirmed that the expert panel's aggregated judgments yielded a Consistency Ratio well below this threshold. This result provides strong validation that the experts' comparisons were logical, reliable, and not random, thereby ensuring a trustworthy foundation for the final calculated weights.

4. Final Weight Calculation: The aggregated matrix, once verified for consistency, was processed to derive the final weights for each of the seven main safety categories. The weights, which represent the normalized principal eigenvector of the matrix, were calculated using Expert Choice software. The analysis of the expert panel's judgments resulted in a final Consistency Ratio (CR) of 0.07, which is well below the 0.10 threshold, confirming the reliability of the derived weights. The final calculated weights for the main categories, which directly reflect the expert panel's collective judgment of their relative importance to overall tunnel safety, are presented in Table 5.

**Table 5. Tunnel Safety Criterion Weighting Table**

| Main Safety Category | AHP Derived Weight ($W_i$) |
|---|---|
| Traffic management and surveillance | 0.237 |
| Emergency and rescue systems | 0.210 |
| Tunnel and road geometry | 0.189 |
| Lighting and power supply | 0.143 |
| Ventilation systems | 0.081 |
| Fire resistance and protection | 0.075 |
| Communication systems | 0.064 |
| Total | 1.000 |

This same AHP procedure was repeated for the sub-criteria within each main category to determine their local weights (Wij). These derived weights (W and Wij) are fundamental inputs for the overall Tunnel Safety (TS) index calculation, as detailed in the result section.

## 4. Results

This section presents the study's primary outcomes, beginning with the application of the developed safety model and the prioritization of safety factors. It then discusses the broader implications and inherent limitations of the model and proposes best practices for its real-world application.

### 4.1. The Final Integrated Safety Model

The weights determined through the AHP process (Table 5) are incorporated into the general safety index formula (Equation 2) to yield the specific final model for this study. The resulting comprehensive equation for calculating the base Tunnel Safety (TS) score is:

$$TS = 0.19\, S_{Geometry} + 0.24\, S_{Traffic} + 0.06\, S_{Communication} + 0.08\, S_{Fire} + 0.21\, S_{Emergency} + 0.08\, S_{Ventilation} + 0.14\, S_{Lighting} \quad (4)$$

where $S_i$ denotes the performance score (0-10) for each of the seven main safety categories, which is an aggregation of the scores of its sub-factors.

To apply this model, a field inspection must first be conducted for each tunnel, and each safety parameter influencing performance should be assigned a performance score. The base TS is then calculated using Equation 4. To ensure a more realistic and conservative safety estimation, this calculated base index must then be multiplied by the tunnel's corresponding Safety Factor (S.F.) from Table 3 to yield the Final Tunnel Safety Index ($TS_{final}$).

### 4.2. Interpretation of Results and Safety Level Classification

The model's final output is a numerical score ($TS_{final}$) ranging from 0 to 10. To provide a practical interpretation of this score, a safety level classification system is defined. Scores closer to 10 indicate superior safety performance. Table 6 defines these safety levels, with a score of 6 or higher ("Good" operation or better) considered acceptable.

**Table 6. Safety level classification**

| Score Range | Condition | Interpretation |
|---|---|---|
| $8 < S \leq 10$ | Perfect | All systems are fully operational and exceed standard requirements. |
| $6 < S \leq 8$ | Good | Systems are well-maintained and function as designed. Minor improvements may be possible. |
| $4 < S \leq 6$ | Mean | Basic safety requirements are met, but several areas show deficiencies that require attention. |
| $2 < S \leq 4$ | Weak | Significant deficiencies exist in multiple safety systems. Corrective action is urgently needed. |
| $0 \leq S \leq 2$ | Very bad | Critical systems are inoperative or absent. The tunnel poses a high risk to users. |

### 4.3. Prioritization of Safety Factors

A primary outcome of the AHP analysis is a clear, quantitative basis for prioritizing safety improvements and guiding resource allocation. The final derived weights, detailed in Table 4, reveal a distinct hierarchy of influence among the seven main safety categories. The complete distribution of these weights, illustrating the relative contribution of each factor to overall tunnel safety, is visualized in Figure 3.

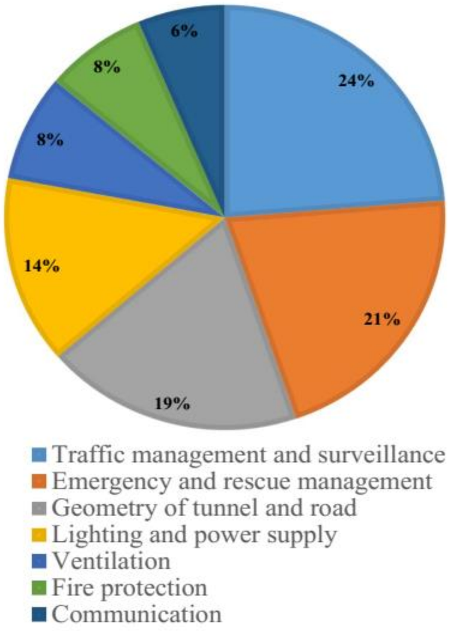


**Figure 3. Relative Importance (Weights) of Main Safety Categories Derived from AHP**

The results show that a majority of the influence is concentrated in three key areas. Traffic Management and Surveillance is the most critical factor, accounting for the largest share of importance with a weight of 24%. This is closely followed by Emergency and Rescue Management (21%) and Tunnel and Road Geometry (19%). Combined, these three categories constitute nearly two-thirds (64%) of the total weight, underscoring their paramount importance in the safety model.

The remaining factors, while essential for a comprehensive safety system, have a lesser relative impact on the final index score. These include Lighting and Power Supply (14%), Ventilation (8%), Fire Protection (8%), and Communication (6%).

This data-driven prioritization is critical for strategic decision-making. Since economic and logistical constraints often make it unfeasible to upgrade all systems simultaneously, this model provides a clear roadmap. It demonstrates that investing in the performance and enhancement of the top-three high-weight categories will yield the most significant and efficient improvements in a tunnel's overall safety score.

To enhance tunnel safety, improving the performance of safety factors is essential. Investigations indicate that improving all factors is not feasible given investment constraints and economic inefficiencies; therefore, the factors have been prioritized. The obtained results indicate that among the factors affecting safety, traffic management and surveillance, emergency service management, and tunnel/road geometry - with respective shares of 24%, 21%, and 19% - have the greatest impact. Consequently, improvements in these factors yield better tunnel safety outcomes.

The results identify the factors that play a critical role in tunnel safety and highlight key parameters that require prioritized attention to achieve significant safety improvements. However, a crucial observation emerges: although low-weight parameters such as ventilation systems contribute minimally to composite safety assessments, the complete failure or functional absence of ventilation in a tunnel can critically compromise safety conditions.

Another critical issue arises when two tunnels (A and B) achieve identical final safety scores, despite significant differences in the distribution of scores across their respective safety categories. Tunnel A demonstrates superior and more acceptable safety performance due to its consistent and uniform scores across all categories. In contrast, Tunnel B may fail to achieve satisfactory safety levels despite excessive investments in high-scoring categories, while neglecting underperforming ones. Nevertheless, the proposed model assigns the same composite score to both tunnels.

These findings highlight the need to account for deviations from mean category scores in tunnel safety assessments. Even when a tunnel's overall score is deemed acceptable, it remains essential to: Monitor score dispersion across categories, identify critically low-scoring parameters, and implement targeted improvements if multiple deficiencies are detected.

## 5. Discussion

The results of this study provide a quantitative framework for tunnel safety evaluation, but a comprehensive interpretation requires discussing its practical implications and the inherent limitations of the model.

### 5.1. Implications for Safety Management and Resource Allocation

To enhance tunnel safety, improving the performance of the most effective safety factors is essential. As investigations show, attempting to improve all factors simultaneously is often infeasible due to the required investment and resulting economic inefficiency. Therefore, the prioritization derived from the AHP model is essential. The results, visualized in Figure 3, indicate that Traffic Management and Surveillance (24%), Emergency and Rescue Management (21%), and Tunnel and Road Geometry (19%) have the greatest impact. Consequently, performance improvements and investments targeting these high-weight factors will yield the greatest returns in enhancing overall tunnel safety.

### 5.2. Model Limitations and Nuances

While the model identifies factors that play a critical role in tunnel safety, it is important to acknowledge its nuances. A crucial observation emerges when considering low-weight parameters. Although ventilation (8%) contributes minimally to the composite safety index, its complete failure or functional absence in a tunnel can, by itself, create critically unsafe conditions, especially during a fire. The model's weighted average structure may not fully capture the catastrophic potential of a "single point of failure" in a low-weight category.

Another critical issue arises from the aggregation method itself. Two tunnels (Tunnel A and Tunnel B) can achieve identical final safety scores despite significant differences in their performance distributions. For instance, Tunnel A might have consistent, acceptable scores across all categories, indicating balanced safety performance. In contrast, Tunnel B could achieve the same final score by having exceptionally high performance in a few high-weight categories while dangerously neglecting others. In its basic form, the proposed model would assign the same composite score to both.

These findings highlight the necessity of looking beyond the final index score and considering score deviations across categories in a safety assessment. Even when a tunnel's overall score is deemed acceptable, it remains essential for safety managers to:

• Monitor the dispersion of scores across all safety categories.

• Identify any critically low-scoring parameters, regardless of their weight.

• Implement targeted improvements to address specific deficiencies, particularly if multiple low scores are detected.

This deeper analysis ensures that the model is used not only as a scoring tool but also as a comprehensive diagnostic framework to achieve genuinely balanced and robust tunnel safety.

## 6. Case study: Application of the Tunnel Safety Model to the Shohada-ye-Gaza Tunnel

To validate the practical applicability and diagnostic power of the proposed Tunnel Safety model, a case study was conducted on the Shohada-ye-Gaza Tunnel. This major urban tunnel (Figure 4), located on the Shahid Hamedani Expressway in Tehran, Iran, was selected for its strategic importance to the city's transportation network, its high traffic volume, and its complex operational environment, making it an ideal candidate for a comprehensive safety evaluation.Tunnel Characteristics and Data Collection

The Shohada-ye-Gaza Tunnel is a twin-tube urban tunnel with a length of approximately 1,100 meters. As a critical artery on the Shahid Hamedani Expressway, it consistently experiences high traffic density characteristic of a major metropolitan transport network. Therefore, its average daily traffic volume exceeds 2,000 vehicles per lane. According to the classification system presented in Table 1, these characteristics ($L > 1000m$, Traffic Volume $\geq 2000$ veh/lane/day) place it in Tunnel Classification 2, signifying a high-risk profile that demands stringent safety standards.

A field inspection was performed on September 20, 2025, by the research team. The assessment was guided by a detailed checklist derived from the hierarchical structure of the provided safety model, which comprises 7 main criteria and 28 constituent sub-factors. The evaluation process involved a combination of direct visual inspection and a review of available operational documentation. Following this systematic investigation, an operational score ($S_i$ ), on a scale from 1 (Very Poor) to 10 (Excellent), was assigned to each of the 28 individual sub-factors.

### 6.1. Calculation of the Tunnel Safety for the Shohada-ye-Gaza Tunnel

Following the field inspection and scoring of each of the 28 safety sub-factors, the Tunnel Safety Index for the Shohada-ye-Gaza Tunnel was computed. The calculation was performed by applying the core TS formula, which aggregates the performance scores of each sub-factor, weighted by their relative importance as determined by the AHP analysis. For each sub-factor (i), its assigned operational score ($S_i$) on a scale of 1 to 10 was multiplied by its predetermined global weight ($W_i$). These individual weighted scores were then summed to produce the final TS value. Table 7, presented at the end of this study, provides a comprehensive breakdown of this calculation, listing the global weight and the assigned score for each sub-factor, as well as the resulting weighted score ($W_i \times S_i$).

**Figure 4. An interior view of the Shohada-ye-Gaza Tunnel**

The initial calculation, based on the weighted sum of the 28 sub-factor scores, yielded a raw Tunnel Safety Index of 6.57 for the Shohada-ye-Gaza Tunnel. However, to account for the inherent risks associated with its specific characteristics, this score must be adjusted. As established in Table 3 (Safety factors based on tunnel classification), the Shohada-ye-Gaza Tunnel falls under Tunnel Classification 2, which requires the application of a safety adjustment factor of 0.89. Multiplying the raw Tunnel Safety by this factor ($6.57 \times 0.89$) results in a final, risk-adjusted safety score of 5.85.

**Table 7. Calculation of the Tunnel Safety for the Shohada-ye-Gaza Tunnel**

| Factor | Sub-Factor | Sub-factor weight | Score | Main category Weight | Final Score |
|---|---|---|---|---|---|
| Geometry of the tunnel and road | Road alignment | 0.314 | 8 | 0.19 | 2.512 |
| | The width of traffic lanes | 0.049 | 8 | | 0.392 |
| | Parking and emergency lanes | 0.276 | 7 | | 1.932 |
| | emergency walkway | 0.171 | 6 | | 1.026 |
| | Cross section | 0.084 | 8 | | 0.672 |
| | Other features | 0.106 | 7 | | 0.742 |
| Traffic management and traffic surveillance | Control center | 0.398 | 3 | 0.24 | 1.194 |
| | Automatic detection of incident and congestion | 0.091 | 2 | | 0.182 |
| | Traffic control | 0.206 | 4 | | 0.824 |
| | Speed and overpass limits | 0.125 | 4 | | 0.5 |
| | Measures for Tunnel Closure | 0.064 | 4 | | 0.256 |
| | Other Facilities | 0.116 | 3 | | 0.348 |
| Emergency and rescue management | Escape and rescue routes | 0.401 | 5 | 0.21 | 2.005 |
| | Regular training for tunnel control center staff and other organizations | 0.104 | 3 | | 0.312 |
| | Emergency response plans | 0.170 | 3 | | 0.51 |
| | Measures in the case of an accident or fire | 0.245 | 4 | | 0.98 |
| | Additional measures | 0.08 | 3 | | 0.24 |
| Fire protection | Fire protection of the tunnel structure | 0.459 | 6 | 0.08 | 2.754 |
| | Fire fighting systems and equipment | 0.459 | 6 | | 2.754 |
| | Drainage system | 0.111 | 7 | | 0.777 |
| | Fire detection and alarm systems | 0.164 | 6 | | 0.984 |
| Communication | Loudspeakers | 0.141 | 6 | 0.21 | 0.846 |
| | Radio for drivers | 0.217 | 7 | | 1.519 |
| | Emergency phones | 0.398 | 8 | | 3.184 |
| | Alarm | 0.156 | 5 | | 0.78 |
| | Other systems | 0.087 | 5 | | 0.435 |
| Ventilation | - | | 7 | 0.08 | 0.56 |
| Lighting and Power supply | - | | 7 | 0.14 | 0.98 |
| **Final Tunnel Safety Score** | | | | | **6.57** |

According to the scoring guidelines defined in Table 2, this final score places the tunnel's operational condition in the "mean" category. While this score provides a clear, high-level benchmark, the model's primary value lies in its diagnostic utility. By analysing the individual weighted scores from the initial assessment, tunnel operators can precisely identify the areas of weakest performance—specifically, sub-factors under 'Traffic management and traffic surveillance', the most critical areas requiring immediate attention and investment to enhance the overall safety of the tunnel.

### 6.2. Sensitivity Analysis

To further illustrate the model's value as a strategic planning tool, a sensitivity analysis was conducted. This analysis explores how targeted safety improvements can translate into a tangible increase in the tunnel's overall safety rating.

The case study identified 'Traffic Management and Traffic Surveillance' as the most critical area for improvement, given its high importance weight and suboptimal performance. We therefore modelled a realistic scenario in which focused investment and operational upgrades yield a 30% improvement in the performance of this single category. The analysis shows that this targeted enhancement would be highly effective. By focusing resources solely on this high-impact area, the final, risk-adjusted Tunnel Safety Index for the Shohada-ye-Gaza Tunnel would increase from 5.85 to 6.03.

This result is significant, as it would elevate the tunnel's safety classification from "Mean" to "Good". This sensitivity analysis demonstrates the model's practical power, enabling authorities to forecast the positive outcomes of strategic investments and providing a clear, data-driven path to achieving a higher standard of safety.

## 7. Author Contributions

Sajad Sepahvand: Conceptualization; Data curation; Formal analysis; Methodology; Resources; Review & Editing.

Seyed Jafar Hejazi: Project administration; Supervision;

Mohammad Hossain Jalal Kamali: Investigation; Data curation; Methodology; Resources; Original draft; Review & Editing.

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