Risk Assessment and Response Prioritization for Railway Tunnels Using Integrated Fuzzy FMEA, CRITIC, and Fuzzy MARCOS Methods

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Abstract: This study presents a comprehensive framework for assessing and prioritizing risks associated with railway tunnels, focusing on the Tehran-North railway in Iran. By integrating fuzzy Failure Modes and Effects Analysis with fuzzy Measurement of Alternatives and Ranking according to the Compromise Solution and fuzzy Criteria Importance Through Intercriteria Correlation methodologies, the research provides a robust multi-criteria approach to evaluate key risk factors such as seismic hazards, water ingress, and structural deformations. The analysis emphasized proactive mitigation strategies like seismic retrofitting and advanced monitoring systems, identifying tunnels at 243, 236, and 260 km as high priorities due to significant accident records. Additionally, tunnels at lower elevations were particularly vulnerable to flooding, landslides, and seismic hazards. This research enhances infrastructure risk management by offering actionable insights for resource allocation and retrofitting strategies while setting a foundation for real-time monitoring and artificial intelligence-driven models.

Keywords: Railway Tunnels; Risk assessment; Prioritization; Fuzzy FMEA Fuzzy CRITIC and MARCOS, Infrastructure Risk Management

1 Introduction

Throughout history, the pursuit of comfort and advancement has driven individuals to innovate and improve various aspects of life. Among the many milestones of human achievement, the development of transportation systems stands out as a crucial component in the progress of civilization [1]. Transportation systems, particularly railway networks, are crucial for sustainable development and enhancing living standards, especially in the face of urbanization and population growth [2, 3]. Tunnel construction enhances movement across distances, but presents unique challenges due to geological and operational risks, including earthquakes, water infiltration, and fires [4]. The intricate relationship between natural forces and human activities within tunnel environments necessitates thorough planning, risk assessment, and effective management strategies to ensure the safety and functionality of these critical infrastructures [5]. The primary objective of this paper is to perform a comprehensive risk assessment of tunnel systems, focusing on identifying significant risks encountered during construction and operational phases. Key hazards, such as roof collapses, flooding incidents, fire outbreaks, and ventilation failures, will be analyzed for their impact on tunnel safety. Furthermore, this study aims to propose a robust risk assessment framework that integrates methodologies such as the Analytic Hierarchy Process (AHP) and Failure Modes and Effects Analysis (FMEA) for quantifying and prioritizing these risks [6-8]. Ultimately, using Integrated Fuzzy FMEA, CRITIC, and Fuzzy MARCOS Methods for risk ranking will provide actionable recommendations for mitigating critical threats and enhancing tunnel safety management [9, 10].

2 Risk Identification

Risk assessment and identification are crucial in tunnel construction and operation, separating natural and non-natural risks. Natural risks include uncontrollable geological and environmental phenomena like earthquakes, groundwater levels, and toxic gases [11, 12]. Natural and non-natural hazards can compromise tunnel structural integrity. Natural hazards include animals and unexpected objects, while non-natural hazards involve technical and human factors. Analyzing loads helps identify performance issues and weaknesses, enabling effective retrofitting and maintenance strategies. Issues include water leakage, fire outbreaks, accidents, ventilation, hazardous material transport, and roof collapse [13-15]. Poor design, malfunctioning machinery, or disregard for safety and management procedures often lead to risks that require risk assessment and risk-reduction plans for tunnel functionality and safety [16]. Table 1 summarizes the natural risk identification. Fig. 1 compares the average costs of mitigation and the response to various natural risks. The sources used in Tables 1 and 2 are provided and detailed respectively in [17] with the numbering from [S1] to [S70].

Table 1
Natural Risks Identification [17]

Risk Code	Subject	Mitigation Code	Mitigation method	Estimated cost	Average estimated cost	Expert-Preferred in Country	Reference
R1	Earthquakes and Associated Hazards	M1	Seismic risk assessment and reinforcement of tunnel structure	$200,000 - $500,000	$350,000	Japan, USA, Chile	[S1–S3]
		M2	Installation of earthquake-resistant materials and design	$100,000 - $300,000	$200,000	Turkey, Nepal, USA	[S4,S5]
		M3	Seismic monitoring systems	$50,000 - $100,000	$75,000	Japan, New Zealand	[S6,S7]
R2	Water Ingress	M4	Waterproofing and water management systems	$50,000 - $150,000.	$100,000	UK, Italy, Germany	[S8–S10]
		M5	Pumping systems and water drainage designs	$30,000 - $100,000	$65,000	USA, Switzerland	[S11,S12]
		M6	Tunnel lining improvement and grouting	$20,000 - $80,000	$50,000	China, Japan, Sweden	[S13–S15]
R3	Faults and Tectonic Activity	M7	Risk assessment and fault avoidance planning	$80,000 - $150,000	$115,000	Turkey, Japan, USA	[S16–S18]
		M8	Geotechnical studies and monitoring	$100,000 - $200,000	$150,000	Italy, Chile, Iran	[S19–S21]
R4	Flood Risks	M9	Flood protection and drainage systems	$100,000 - $300,000	$200,000	Netherlands, UK	[S22,S23]
		M10	Flood-resistant tunnel designs and sealing	$200,000 - $500,000	$350,000	Japan, Italy	[S24,S25]
R5	Freezing Conditions	M11	Thermal insulation of tunnel lining	$150,000 - $300,000	$225,000	Canada, Norway	[S26,S27]
		M12	Heating systems for tunnels in freezing environments	$50,000 - $200,000	$125,000	Sweden, Russia	[S28]
R6	Presence of Toxic or Explosive Gases	M13	Ventilation and air circulation systems	$300,000 - $1,000,000	$650,000	USA, Japan, Canada	[S29–S31]
		M14	Gas detection and emergency alert systems	$20,000 - $50,000	$35,000	UK, China, Australia	[S32–S34]
R7	Groundwater Fluctuations	M15	Groundwater monitoring and control systems	$50,000 - $150,000	$100,000	Italy, UK, Germany	[S35–S37]
		M16	Reinforcement of tunnel lining to withstand water pressure	$100,000 - $300,000	$200,000	USA, Japan, Switzerland	[S38–S40]

Risk Code	Subject	Mitigation Code	Mitigation method	Estimated cost	Average estimated cost	Expert-Preferred in Country	
R8	Presence of Animals and Unexpected Objects	M17	Wildlife and debris detection systems	$30,000 – $70,000	$50,000	USA, UK, Australia	[S41–S43]
		M18	Tunnel inspections and maintenance	$10,000 – $50,000	$30,000	Germany, Canada	[S44,S45]
R9	Falling Objects from the Tunnel Ceiling and Walls	M19	Reinforcement of tunnel structure and periodic inspections	$100,000 - $300,000	$200,000	USA, France, UK	[S46–S48]
		M20	Installation of rock bolts and support systems	$50,000 - $200,000	$125,000	Italy, Switzerland	[S49,S50]

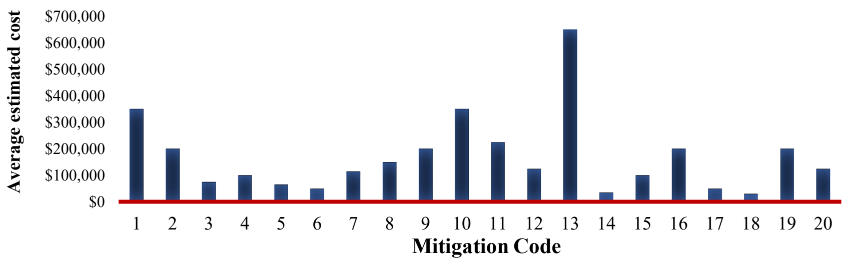


Figure 1

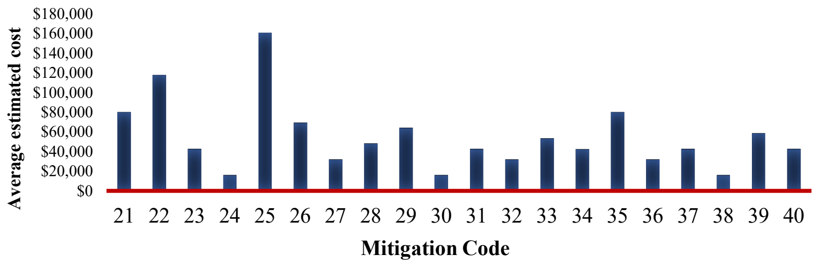
Comparison of the Average Costs of Mitigation and Response to Various Natural Risks

Tunnels, vital to modern infrastructure, face unpredictable risks such as earthquakes, requiring specialized responses. The interaction between seismic forces and geology demands adaptive engineering and high design standards [18, 19]. However, previous studies have not effectively integrated earthquake risk assessment with retrofitting in rail infrastructure, highlighting the need for targeted strategies to enhance resilience. Effective waterproofing and drainage systems are critical for maintaining tunnel integrity [20, 21]. Advanced predictive modeling and real-time monitoring technologies are essential for addressing cracks, misalignments, and disruptions in tunnel linings in geologically volatile areas [22]. Flood risks, exacerbated by erratic weather, threaten tunnels with overflows and damage, making resilient drainage systems and comprehensive flood management plans essential [23]. Freezing conditions further degrade tunnel materials, causing microcracks and structural vulnerabilities, necessitating frost-resistant materials and advanced thermal protection systems [24]. Subterranean toxic gases, such as methane, pose significant safety risks, requiring precise detection and efficient ventilation systems to prevent catastrophic incidents [25]. Seasonal or human-induced groundwater fluctuations can destabilize tunnel foundations, increasing water ingress, which calls for adaptive engineering solutions [26]. Additionally, operational disruptions from animal or debris intrusion can be mitigated through regular inspections and proactive measures [27]. Falling objects from ceilings or walls due to geological instability or maintenance issues underscore the importance of routine checks and high-quality construction materials [28]. Table 2 summarizes the non-natural risk identification. Fig. 2 gives the comparison of the average costs of mitigation and response to various non-natural risks

Table 2
Non-natural Risks Identification [17]

Risk Code	Subject	Mitigation Code	Mitigation method	Estimated cost	Average estimated cost	Expert-Preferred in Country	Reference
R10	Tunnel Roof Collapse	M21	Preventive maintenance and structural reinforcement through early detection using sensors.	$53,500 – $107,000	$80,250	Germany	[S51]
		M22	AI-powered inspection systems are used to detect weaknesses and monitor structural integrity.	$74,900 – $160,500	$117,700	Japan	[S52]
R11	Cross-sectional Deformation and Clearance Reduction	M23	Advanced simulation software for predicting cross-sectional deformations and optimal design.	$32,100 – $53,500	$42,800	Switzerlan d	[S53]
		M24	Regular technician training for early detection and correction of cross-sectional deformations.	$10,700 – $21,400	$16,050	China	[S54]
R12	Tunnel Ventilation Issues	M25	Use of automated intelligent ventilation systems with air quality sensors.	$107,000 – $214,000	$160,500	Norway	[S55]
		M26	Regular monitoring and smart air quality sensors to detect hazardous gases.	$53,500 – $85,600	$69,550	Italy	[S56]
R13	Transport of Hazardous Materials	M27	Mandatory training for operators on safe transportation and emergency response protocols.	$21,400 – $42,800	$32,100	USA	[S57]
		M28	Implementation of advanced tracking systems to monitor hazardous material transport in tunnels.	$32,100 – $64,200	$48,150	France	[S58]
R14	Fire	M29	Installation of fire suppression systems, like sprinklers and foam.	$21,400 – $107,000	$64,200	UK	[S59]
		M30	Regular fire drills and emergency response training for tunnel operators.	$10,700 – $21,400	$16,050	Australia	[S60]
R15	Accidents During Rail Operation	M31	Implementation of automatic train control and collision avoidance systems.	$32,100 – $53,500	$42,800	South Korea	[S61]
		M32	Frequent safety audits and operator training programs to reduce human error.	$21,400 – $42,800	$32,100	Spain	[S62]
R16	Lateral and Vertical Track Displacement	M33	Use of advanced geotechnical monitoring systems to detect track displacement.	$42,800 – $64,200	$53,500	Canada	[S63]
		M34	Regular maintenance and timely realignment of tracks in response to detected displacement.	$32,100 – $53,500	$42,550	Russia	[S64]
R17	Wate r Leak age	M35	Installation of advanced waterproofing systems and regular maintenance.	$53,500 – $107,000	$80,250	Italy	[S65]

Risk Code	Subject	Mitigation Code	Mitigation method	Estimated cost	Average estimated cost	Expert-Preferred in Country	Reference
		M36	Use of sensors to detect early signs of water infiltration and prevent damage.	\$21,400 – \$42,800	\$32,100	Brazil	[S66]
R18	Collision with Obstacles Inside the Tunnel	M37	Installation of detection systems and automated alert systems to notify operators.	\$32,100 – \$53,500	\$42,800	USA	[S67]
		M38	Regular inspections and maintenance of tunnel infrastructure to prevent debris build-up.	\$10,700 – \$21,400	\$16,050	Germany	[S68]
R19	Environmental Impact Risks	M39	Implementation of sustainable tunnel operation practices to reduce environmental contamination.	\$42,800 – \$74,900	\$58,850	France	[S69]
		M40	Development of emergency response protocols to handle environmental disasters within tunnels.	\$32,100 – \$53,500	\$42,800	Italy	[S70]



Comparison of the Average Costs of Mitigation and Response to Various Non-Natural Risks

Tunnels, vital infrastructure arteries, face hazards like roof collapse due to structural vulnerabilities or geotechnical instability. Prevention requires rigorous assessments and meticulously designed tunnel linings to withstand stresses, ensuring tunnel integrity and safety [29]. Tunnel cross-section distortion can compromise clearance levels and disrupt traffic flow, potentially leading to traffic bottlenecks, operational inefficiencies, and safety hazards. Proactive monitoring and reinforcement measures are crucial to prevent these risks [30]. Tunnel safety is significantly compromised by inadequate ventilation, leading to the buildup of toxic gases like carbon monoxide and methane, which can pose a life-threatening threat to workers and travelers [31]. Hazardous materials transportation through tunnels poses significant safety risks, including chemical spills, leaks, and explosions. Establishing rigorous protocols, rapid response systems, and emergency containment strategies is crucial for these high-risk operations [32]. Fires in tunnels are dangerous due to limited space and lack of evacuation routes. Implementing fire-resistant materials, advanced suppression systems, and clear, accessible pathways is crucial to reduce their impact [33]. Rail accidents in tunnels can be catastrophic due to space limitations, emergency responder access, and welding defects. Preventive measures like regular maintenance, automated monitoring, and effective signaling protocols are crucial for smooth operation [34-36]. Track displacements caused by soil settlement, poor maintenance, or structural shifts pose significant threats to tunnel integrity and train safety. Rapid detection, correction, and reinforcement are crucial [37]. Water leakage in tunnels can cause structural degradation, necessitating high-quality water leakage, which requires high-quality waterproofing systems and regular inspections. Obstacles can disrupt operations, requiring proactive removal for efficiency and safety. [38, 39]. Tunnel operations in industrial zones pose environmental risks, requiring strict safety standards and regular monitoring. Proactive design, maintenance, and advanced safety systems ensure efficient transportation and communication.

3 Scope of Study

The Tehran-North railway, built during the Pahlavi dynasty, connects central Iran to the Caspian Sea, overcoming geographical challenges. This railway, featuring a network of tunnels, navigates the Alborz Mountains and remains vital to Iran's transportation infrastructure. The Gadook Tunnel exemplifies engineering challenges in the region's complex geology. Tunnels mitigate risks like landslides and seismic vibrations, necessitating thorough risk assessments.

Point/Coordinate	Zone	X	Y	Z
A	39s	619062	3899933	850 m
B	39s	684255	4047230	45 m

The maximum elevation of this railway route is 2,250 meters between Gadook and Veresk stations.

Figure 3
The location of the study corridor within Iran's railway network

Evaluating risks near the Veresk Bridge is essential for ensuring safety and preserving this critical transportation corridor, a landmark of Iranian engineering. Fig. 3 represents the location of the study corridor within Iran's railway network. Tables 3-7 give different statistics on accidents and damages.

Table 3
General Overview of Accidents

Index	Value	Index	Value
Coverage Years	2011-2024	Total Number of Fatalities	0
Most Common Type of Damaged Vehicle	Freight Train	Total Number of Injuries	6 people
The Most Common Type of Accident	Block Exit	Most Common Location of the Accident	Savadkuh - Sorkhabad

Table 4
Classification of Accidents by Severity

The severity of the Accident:	Number of Accidents	Percentage of Total Accidents [%]
Very Important	1	7.69
Level One	2	15.38
Level Two	4	30.76
Level Three	6	46.15

Table 5
Classification of Accidents by Type of Vehicle and Type of Accident

Type of Railway Vehicle	Type of Incident	Number of Incidents
Passenger Train	Exit in Block	3
	Collision with Livestock and Animals	1
	Collision with Pedestrian	1
Freight Train	Exit in Block	6
railway maintenance train	Exit in Block	1
	Collision with Obstacle	1

Table 6
Geographical Distribution and Incident Damages

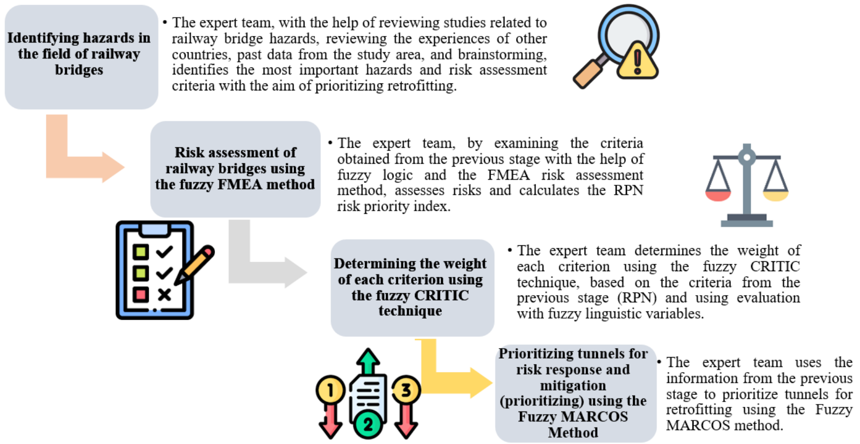
Type of Incident	Origin-Destination	Kilometer (Start)	Total Damage	damage categories	Type of Track
Exit in Block	Sorkhabad to Veresk	253	920,400.88$	High damage	Block
Exit in Block	Veresk to Do Gol	243	367,419.05$	High damage	Block
Exit in Block	Sorkhabad to Savadkouh	259	17,404.83$	Medium damage	Block
Exit in Block	Savadkouh to Sorkhabad	259	16,912.43$	Medium damage	Block
Exit in Block	Sorkhabad to Savadkouh	260	10,155.71$	Medium damage	Block
Exit in Block	Sarakhabad to Veresk	248	9,333.57$	Medium damage	Block
Exit in Block	DoGol to Gadook	224	4,468.95$	Low damage	Block
Exit in Block	Savadkouh to Sorkhabad	260	3,864.23$	Low damage	Block
Exit in Block	Savadkouh to Sorkhabad	260	2,537.26$	Low damage	Block
Collision with Obstacle	Shirgah to Sirab	310	125.57$	Very low damage	Block
Exit in Block	DoGol to Veresk	236	0$	No damage	Block
Collision with Animals	Gadook to Do Gol	219	0$	No damage	Non-block
Collision with Pedestrian	Zarrindasht to Mahabad	180	0$	No damage	Non-block

Table 7
Details of Damages and Causes of Accidents

Criteria	Number of Cases	Percentage	Description
Exit in Block	10	76.9%	The highest number of accidents due to track and equipment failure
Exit in Block	1	7.7%	Related to non-compliance with human regulations
Collision with Livestock and Animals	1	7.7%	Associated with environmental conditions and improper control
Collision with Pedestrian	1	7.7%	Resulting from unauthorized entry into the railway boundary
Primary Cause			
Track	7	53.8%	The most important factor in the occurrence of accidents
Human Resources	2	15.4%	Indicates the need for more training and supervision
Freight Wagon	2	15.4%	Technical failure and issues related to the wagon
Other Rail Vehicles	1	7.7%	Related to specific equipment
Miscellaneous	1	7.7%	Collision with animals
First Cause			
Line breakdown or technical fault	4	30.8%	Need for better track maintenance
Technical fault in the wagon	2	15.4%	Equipment-related issues
Failure to follow human regulations	2	15.4%	Inadequate training or negligence
Shock to the train or environmental factors	2	15.4%	*
Unauthorized entry into the track area or environment	2	15.4%	Control issues along the route
Other reasons	1	7.7%	*

4 Risk Analysis of Railway Tunnels Using Fuzzy FMEA and Logic in Northern Directorate

This study employs the fuzzy FMEA method to evaluate and prioritize risks in 10 key tunnels of the Northern Iranian Railway, considering severity, occurrence, non-detection, criticality for transportation continuity, and infrastructure conditions. The methodology encompasses risk identification, quantitative analysis, and mitigation planning, leveraging fuzzy CRITIC and MARCOS methods for weighting and prioritization. Fig. 4 outlines research steps for assessing risks and retrofitting railway bridges.



Outline of research steps for assessing risks and retrofitting railway bridges

Risk management is divided into three stages: Risk Identification, Qualitative Risk Analysis, and Risk Response Planning, ensuring a thorough assessment and effective response to maintain railway tunnel safety and reliability. Expert opinions guide the evaluation based on the RPN criterion to prioritize tunnel retrofitting. The framework involves assembling an expert team with rail transport infrastructure experience to analyze risks using fuzzy FMEA, determine criterion weights through fuzzy CRITIC, and establish retrofitting priorities via the fuzzy MARCOS technique. This study introduces significant innovations by integrating risk assessment with retrofitting prioritization for the Northern Railway General Directorate. Unlike previous research that primarily focused on risk evaluation, this study emphasizes actionable responses and prioritization, enhancing the safety and reliability of railway bridges and tunnels. The study uses a hybrid model based on fuzzy logic, including fuzzy CRITIC and fuzzy MARCOS multi-criteria decision making techniques. This approach simultaneously analyzes qualitative and quantitative criteria by considering uncertainties and ambiguities in the data. Unlike traditional methods that lack a comprehensive view of all aspects related to the retrofitting of railway bridges, the proposed model provides a more comprehensive and multi-criteria assessment of railway bridge hazards. The previous section introduced the most important criteria for assessing railway bridge risks. The following sections will introduce the approaches to assessing risks using fuzzy FMEA and weighting criteria (fuzzy CRITIC) and then discuss how to prioritize them with fuzzy logic (fuzzy MARCOS).

4.1 Formation of an Expert Team

In this study, the authors emphasize the importance of forming an expert team (EX) with experience in seismic hazards, railway construction, and maintenance to assess risks and retrofitting criteria. Experts' opinions are quantified using triangular fuzzy numbers, considering varying expertise and reducing bias. In step one, the team evaluates seismic risks, and in step two, they assess retrofitting criteria using linguistic terms converted into fuzzy numbers, detailed in Table 8 and Figure 5.

Table 8
Linguistic scales for expert team judgment and Fuzzy number

Abbreviation	Linguistic variables	Fuzzy number
VL	Very Low	(0,0,0.1)
L	Low	(0,0.1,0.3)
ML	Medium Low	(0.1,0.3,0.5)
M	Medium	(0.3,0.5,0.7)
MH	Medium High	(0.5,0.7,0.9)
H	High	(0.7,0.9,1)
VH	Very High	(0.9,1,1)

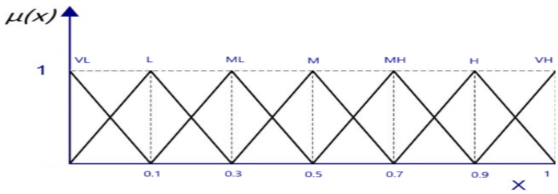


Figure 5
Display of triangular fuzzy numbers equivalent to each of the linguistic variables in Table 8

After completing the questionnaire by the expert members (EX), the criteria are collected, and the results are converted into triangular fuzzy numbers in the form of the matrix as Eq. (1).

4.2 Risk Assessment using the Fuzzy Logic and Failure Mode and Effects Analysis (FMEA) Method

Risk analysis significantly enhances analytical validation by assessing potential failures. Failure Modes and Effects Analysis (FMEA) is a key risk analysis tool that improves risk management. It is a qualitative method used to mitigate risks during the design phase before they materialize, originating from NASA's studies in 1963. The outcomes of FMEA assist managers and engineers in identifying failure modes, understanding their causes, and addressing them during the design and production stages. This facilitates more effective risk management decision-making. Each FMEA includes Failure Mode, Failure Cause, Failure Effects, and Detection Methods [40]. A risk priority number (RPN) is a method to assess the risks linked to potential issues identified in an FMEA [41]. In conventional FMEA, RPN evaluates risk based on three factors: Occurrence (O), Severity (S), and Detection (D), each rated on a scale from 1 to 10. RPN is used to prioritize failure modes and is determined using Eq. (1).

$$RPN = O \times S \times D. \quad (1)$$

Greater attention is required for higher RPN values. The occurrence criterion reflects the likelihood of a failure mode, with '1' representing low probability and '10' indicating high probability. Severity measures the impact of a failure mode, where '1' signifies negligible impact and '10' denotes a life-threatening impact. Detection refers to identifying the potential cause of a failure mode, with '1' indicating it is sure to be detected and '10' indicating it is impossible to detect. This study presents a fuzzy logic-based methodology for prioritizing failures within a system FMEA. Linguistic terms were employed to describe Occurrence (O), Severity (S), Detection (D), and the associated risks of failures, thereby addressing the limitations of the traditional RPN approach. This paper's proposed method includes risk identification, qualitative risk analysis, and risk response planning. The steps of the authors' method are as follows. In the first step, the identification of the railway tunnel risk was done, as in Section 2, see Tables 1 and 2. The definition of fuzzy membership functions for each risk's final RPN is as very low (VL), low (L), Medium Low (ML), medium (M), Medium High (MH), high (H), and very high (VH) as presented as Linguistic scales for expert team judgment and Fuzzy number in Table 1. In the second step, the occurrence of the fuzzy number ($\tilde{O}_{ij}$), severity ($\tilde{S}_{ij}$), and non-detection ($\widetilde{D}_{ij}$) of railway tunnel i and risk j were determined based on the expert team's estimation. Here, "non-detection" means that the risks are not detectable. The fuzzy RPN was calculated using Eq. (2) in the third step.

$$\widetilde{RPN}_{ij} = \tilde{O}_{ij} \otimes \tilde{S}_{ij} \otimes \widetilde{D}_{ij} \tag{2}$$

In the fourth step, the weights of the degree of criticality of the railway tunnels were determined in terms of the possibility of continuing transportation operations in the case when risk j occurs in railway tunnel i ($\widetilde{C_{ıȷ}}$). Finally, in the fifth step, the weights of the current state of the infrastructure were computed in terms of the state of retrofitting ($\widetilde{A_{ıȷ}}$) of railway tunnel i and risk j. according to Eq. (3), these two values were multiplied by the product of the three remaining criteria, $\widetilde{RPN}_{ij}$, $\widetilde{C_{ıȷ}}$and $\widetilde{A_{ıȷ}}$ which will be the final calculated risk score ($\widetilde{RPN}_l$) for operation d in the next step.

$$\widetilde{RPN}_l = \widetilde{RPN}_{ij} \otimes \tilde{C}_{ij} \otimes \tilde{A}_{ij} \tag{3}$$

4.3 Weighting of Criteria based on the Fuzzy CRITIC Method

In multi-criteria decision making, two main issues were faced: weighing criteria and ranking options, which are complementary. The study collects expert opinions on FMEA fuzzy evaluation, using the fuzzy CRITIC method to weigh RPN criteria, followed by the fuzzy Marcus method to prioritize tunnel construction. The CRITIC method, suitable for calculating criteria weight, considers the decision-makers's subjective perspectives and criteria characteristics. Weights formed by experience, knowledge, and understanding of the problem can raise reliability concerns. Numerical valuation approaches address this issue. Introduced by Zelini in 1982 and developed further by Diakoulaki et al. in 1995, the CRITIC method analyzes data based on interference and conflict between factors, ensuring each factor's correct role in the final calculations. Each evaluation criterion has a range of changes expressed as a membership function, with statistical parameters like standard deviation representing discrepancies in criteria values. The CRITIC method objectively determines criteria weights, accounting for conflict and incompatibility in decision problems. The first step in implementing this method involves forming a decision matrix as Eq. (4).

$$\tilde{X} = \tilde{x}_{ij} = \left[x_{ij}^{l}, x_{ij}^{m}, x_{ij}^{u}\right] = \begin{bmatrix} \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad \forall \begin{cases} i = 1,2,\ldots,m \\ j = 1,2,\ldots,n \end{cases} \tag{4}$$

Then, with the help of Eqs. (5-6), the initial decision matrix was normalized in the previous step. In Eqs. (5-6), B represents profit criteria, and C represents cost criteria.

$$\tilde{r}_{ij} = \frac{\tilde{x}_{ij}}{\tilde{x}_{j}^{max}} \quad \forall j \in B \tag{5}$$

$$\tilde{r}_{ij} = \frac{\tilde{x}_{j}^{min}}{\tilde{x}_{ij}} \quad \forall j \in C \tag{6}$$

The next step, after calculating the values of the standard deviation and linear correlation of the matrix by columns, is to determine the amount of information ($\tilde{C}_j$) about each criterion j in Eq. (7) (where $\tilde{\sigma}_j$ is the standard deviation, and $\tilde{r}_{ij}$ is the linear correlation coefficient for the criteria).

$$\tilde{C}_j = \tilde{\sigma}_j \sum_{i=1}^{m}\left(1 - \tilde{r}_{ij}\right) \tag{7}$$

Finally, the weight of each criterion can be calculated according to Eq. (8).

$$\widetilde{w}_j = \frac{\tilde{C}_j}{\sum_{j=1}^{n} \tilde{C}_j} \tag{8}$$

In the next section, fuzzy logic is used to evaluate and prioritize tunnels based on the most important effective risks to prepare the infrastructure as a response to risks.

4.4 Prioritizing Tunnels for Risk Response and Mitigation using the Fuzzy MARCOS Method

The fuzzy MARCOS method is one of the most widely used multi-criteria decision making (MCDM) methods, introduced by Stević and colleagues in 2020 [42]. It ranks options under study using inputs like the decision matrix, criteria weights, and the nature of criteria regarding positivity and negativity [43]. The method considers positive and negative ideals from the start, examining their relationship with alternative options and describing the utility degrees of the options. By summing the weights, the weighted matrix for absolute value is calculated based on Eqs. (9-11).

$$\tilde{V}_{ij} = \widetilde{w}_j \times \tilde{r}_{ij} \tag{9}$$

$$\tilde{S}_j = \sum_{j=1}^{n} \tilde{v}_{ij} \tag{10}$$

$$S_i = \frac{S_j^l + S_j^m + S_j^u}{3} \tag{11}$$

Then, using Eqs. (12) and (13), the degree of utility was calculated for the positive and negative ideals.

$$UD_i^{(AI)} = \frac{S_i}{S^{(AI)}} \tag{12}$$

$$UD_i^{(AAI)} = \frac{S_i}{S^{(AAI)}} \tag{13}$$

Then, the utility functions of the decision options are calculated by considering the positive and negative ideals according to Eqs. (14) and (15).

$$UF_i^{(AI)} = \frac{UD_i^{(AAI)}}{UD_i^{(AI)} + UD_i^{(AAI)}} \tag{14}$$

$$UF_i^{(AAI)} = \frac{UD_i^{(AI)}}{UD_i^{(AI)} + UD_i^{(AAI)}} \tag{15}$$

Finally, the ranking of options based on the values of the ideal positive and ideal negative utility functions can be calculated as follows according to Eq. (16).

$$UF_i = \frac{\left(UF_i^{(AI)} + UF_i^{(AAI)}\right)}{1 + \left(\frac{UF_i^{(AI)}}{UF_i^{(AAI)}}\right) + \left(\frac{UF_i^{(AAI)}}{UF_i^{(AI)}}\right)} \tag{16}$$

So, based on the utility of each tunnel, the railway tunnels were prioritized for risk response and mitigation.

5 Risk Assessment and Response Prioritization for Key Railway Tunnels in Northern Iran Using Integrated Fuzzy FMEA, CRITIC, and Fuzzy MARCOS Methods

In this section, using the fuzzy FMEA technique and fuzzy linguistic variables, the authors use expert opinions to evaluate each tunnel. The evaluation employs triangular fuzzy numbers, which are preferable to definite numbers. The fuzzy Delphi method, which integrates Delphi and fuzzy theory, works better for this evaluation. A questionnaire assigns average scores to each criterion and tunnel, with experts choosing from seven linguistic words. At this stage, the authors provide experts with information from their visits to evaluate and prioritize based on FMEA criteria and two other criteria: the degree of criticality of railway tunnels regarding the possibility of continuing transportation operations in the case when risk occurs ($\tilde{C}$) and the current state of the infrastructure in terms of the state of retrofitting ($\tilde{A}$) of railway tunnels. As can be seen, these infrastructures include 10 tunnels.

The evaluation of the expert team with the help of linguistic variables according to Table 9 has been carried out on a Likert scale as very low (VL), low (L), Medium Low (ML), medium (M), Medium High (MH), high (H), and very high (VH), and the result of a sample of the expert team's opinions is shown in Table 9.

Table 9
Sample of expert team opinions for evaluating $\tilde{O}, \tilde{S}, \widetilde{D}, \tilde{C}$and $\tilde{A}$ assignment of risks of tunnels

Tunnels / Risk assessment criteria	Risk items	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
Km 253 tunnel	$\tilde{O}$	ML	ML	L	L	VL	VL	VL	M	ML	VL	VL	M	M	VL	L	VL	M	VL	M
	$\tilde{S}$	M	ML	ML	ML	L	MH	ML	L	M	H	M	MH	VL	ML	ML	M	L	H	M
	$\widetilde{D}$	MH	M	L	ML	L	VL	VL	M	L	VL	VL	VL	VL	L	M	VL	VL	L	VL
	$\tilde{C}$	MH	ML	VL	M	VL	VL	VL	M	VL	VL	L	L	L	ML	M	VL	L	ML	VL
	$\tilde{A}$	MH	ML	M	MH	MH	ML	M	ML	MH	MH	ML	H	ML	MH	MH	ML	ML	M	ML
Km 243 tunnel	$\tilde{O}$	M	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	H	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	H	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	MH	M	M	M	L	L	L	H	L	VL	L	L	VL	L	VH	VL	VL	L	VL
	$\tilde{A}$	M	H	M	H	M	ML	MH	ML	H	ML	MH	MH	M	M	MH	H	MH	M	ML
Km 259 tunnel	$\tilde{O}$	MH	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	H	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	VH	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	VH	H	M	ML	L	VL	VL	M	L	VL	VL	L	VL	L	H	VL	L	VL	L
	$\tilde{A}$	ML	ML	ML	M	MH	ML	MH	M	M	ML	H	MH	M	MH	M	MH	ML	H	ML
Km 260 tunnel	$\tilde{O}$	MH	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	H	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	VH	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	VH	MH	ML	M	M	VL	VL	MH	L	L	VL	VL	VL	VL	VH	VL	L	VL	VL
	$\tilde{A}$	MH	M	H	M	MH	M	M	M	ML	ML	H	M	ML	M	M	MH	H	H	ML
Km 248 tunnel	$\tilde{O}$	L	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	ML	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	M	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	M	H	M	MH	ML	L	VL	MH	L	VL	VL	VL	VL	L	VH	VL	VL	L	L
	$\tilde{A}$	M	M	M	MH	H	ML	M	H	MH	H	MH	ML	M	ML	MH	MH	ML	M	MH
Km 224 tunnel	$\tilde{O}$	M	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	MH	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	H	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	VH	H	ML	ML	L	L	VL	H	ML	VL	VL	VL	VL	ML	H	VL	VL	VL	VL
	$\tilde{A}$	M	M	MH	MH	M	MH	M	H	ML	H	MH	H	H	ML	H	H	MH	H	M
Km 310 tunnel	$\tilde{O}$	M	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	MH	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	H	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	MH	MH	L	M	ML	VL	VL	M	M	VL	L	VL	VL	VL	H	VL	L	VL	VL
	$\tilde{A}$	M	M	H	ML	M	H	MH	ML	MH	M	ML	MH	H	MH	MH	M	H	H	M
Km 236 tunnel	$\tilde{O}$	M	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	H	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	VH	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	H	M	M	ML	L	L	VL	H	M	VL	L	VL	VL	VL	H	VL	VL	L	L
	$\tilde{A}$	ML	M	H	ML	H	M	MH	ML	H	M	ML	H	MH	H	H	H	H	M	H
Km 219 tunnel	$\tilde{O}$	ML	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	M	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	M	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	MH	M	L	M	M	L	L	M	M	VL	L	L	L	ML	VH	VL	VL	L	VL
	$\tilde{A}$	M	M	H	H	ML	M	H	ML	M	M	H	M	ML	M	ML	M	ML	ML	M
Km 180 tunnel	$\tilde{O}$	ML	M	L	ML	VL	VL	VL	MH	M	VL	VL	H	H	VL	L	VL	MH	VL	H
	$\tilde{S}$	M	M	M	M	L	H	M	L	H	VH	H	H	VL	M	M	H	L	VH	MH
	$\widetilde{D}$	M	MH	ML	M	ML	VL	VL	MH	ML	VL	VL	VL	VL	L	H	VL	VL	L	VL
	$\tilde{C}$	ML	M	L	MH	L	L	L	MH	L	VL	VL	L	VL	L	H	VL	VL	ML	VL
	$\tilde{A}$	H	MH	ML	MH	M	MH	ML	MH	MH	MH	ML	MH	M	H	ML	M	MH	H	M

In Table 9, the RPN value can be calculated by calculating the fuzzy multiplication of three triangular numbers. $\tilde{O}, \tilde{S}$ and $\widetilde{D}$. This value, along with the two criteria $\tilde{C}$ and $\tilde{A}$, are weighted in the next step. This section used the Fuzzy CRITIC and Fuzzy MARCOS techniques to weigh the most important vulnerability criteria of railway tunnels and determine the priority of key bridges for reinforcement, which are responses to risks and mitigations. The expert team, composed of six managers from the North railway region with extensive experience in railway infrastructure, evaluates the criteria. This team includes roles like the general manager, technical and infrastructure deputy, and others. The study considers five risk assessment criteria, focusing on FMEA criteria and two additional ones: the degree of criticality of railway tunnels regarding continuing transportation operations during risks and the current state of infrastructure retrofitting of railway tunnels. Table 10 gives weights of risk items using the Fuzzy CRITIC method.

Table 10
Weights of risk items using the Fuzzy CRITIC method

Risk items	$\widetilde{w}_j$
Earthquakes and Associated Hazards	(1.6,3.21,3.46)
Water Ingress	(0.87,1.73,1.97)
Faults and Tectonic Activity	(0.19,0.37,0.4)
Flood Risks	(0.48,0.95,1.1)
Freezing Conditions	(0.04,0.08,0.08)
Presence of Toxic or Explosive Gases	(0.02,0.05,0.05)
Groundwater Fluctuations	(0.01,0.03,0.03)
Presence of Animals and Unexpected Objects	(0.58,1.15,1.32)
Falling Objects from the Tunnel Ceiling and Walls	(0.49,0.97,1.07)
Tunnel Roof Collapse	(0.02,0.04,0.04)
Cross-sectional Deformation and Clearance Reduction	(0.02,0.05,0.05)
Tunnel Ventilation Issues	(0.14,0.29,0.35)
Transport of Hazardous Materials	(0.02,0.03,0.03)
Fire	(0.04,0.08,0.09)
Accidents During Rail Operation	(0.82,1.64,1.81)
Lateral and Vertical Track Displacement	(0.02,0.04,0.04)
Water Leakage Behind Tunnel Lining	(0.04,0.07,0.08)
Collision with Obstacles Inside the Tunnel	(0.07,0.13,0.15)
Environmental Impact Risks	(0.09,0.19,0.22)

In Table 10, the weight of each risk has been calculated according to the fuzzy CRITIC method. In the next step, according to the fuzzy MARCOS method, calculations can be continued with the help of these weights and the decision matrix according to the defining relationships (AI) and (AAI). Now, by calculating the utility value (UF_i), the priority of each tunnel can be selected for retrofitting, providing an appropriate response to risks and adopting mitigation policies. Table 11 shows the final results of prioritizing tunnel retrofitting using the Fuzzy MARCOS method.

Table 11
Final results of prioritizing tunnel retrofitting using the Fuzzy MARCOS method

Tunnels	UF_i
Km 253 tunnel	0.78
Km 243 tunnel	1.851
Km 259 tunnel	0.218
Km 260 tunnel	0.897
Km 248 tunnel	0.195
Km 224 tunnel	0.719

Km 310 tunnel	0.096
Km 236 tunnel	1.032
Km 219 tunnel	0.228
Km 180 tunnel	0.834

The analysis in Table 11 identifies the Km 243, Km 236, and Km 260 tunnels as the highest priorities for risk response and retrofitting due to their high accident records and associated risks. Tunnels at lower elevations face increased risks, particularly from flooding and inundation. Mountain slopes also pose risks like landslides, erosion, and seismic activity, which threaten tunnel integrity. Effective mitigation measures include structural reinforcements, improved drainage, advanced monitoring technologies, regular maintenance, and developing emergency response plans to safeguard tunnels and maintain reliable railway infrastructure.

Conclusions

This study presents a framework for assessing railway tunnel risks in a mountainous Iranian route by integrating Fuzzy FMEA and MARCOS methodologies. The findings reveal that tailored risk management strategies can significantly enhance the safety and functionality of these infrastructures. The study demonstrated the effectiveness of fuzzy logic in managing uncertainties in risk assessment, offering a more robust evaluation compared to traditional methods. The hybrid model, combining fuzzy CRITIC and fuzzy MARCOS multi-criteria decision making techniques, enabled a comprehensive analysis of fuzzy FMEA criteria, addressing data ambiguities and the limitations of conventional methods lacking a holistic approach to retrofitting priorities. Proactive strategies like seismic retrofitting, advanced ventilation, and modern monitoring were emphasized, prioritizing tunnels at Km 243, Km 236, and Km 260 due to high accident and risk records. Tunnels at lower elevations were noted as vulnerable to flooding, landslides, erosion, and seismic hazards. This research advances infrastructure risk management, offering a foundation for adapting the methodologies to other infrastructures. Future work could integrate real-time monitoring deep learning for pattern recognition and predictive analytics and AI-driven predictive models to further enhance risk assessment and mitigation [44, 45]. Also, future risk assessments should incorporate climate change projections and employ predictive modeling techniques to evaluate long-term impacts.

References

[1] Othman, A. G., & Ali, K. H. (2020) Transportation and quality of life. *Planning Malaysia*, *18*(13) https://doi.org/10.21837/pm.v18i13.774

[2] Kuchak, A. J. T., Marinkovic, D., & Zehn, M. (2021) Parametric investigation of a rail damper design based on a lab-scaled model. *Journal of Vibration Engineering & Technologies*, *9*, 51-60

[3] Kuchak, A. J. T., Marinkovic, D., & Zehn, M. (2020) Finite element model updating–Case study of a rail damper. *Structural Engineering and Mechanics, An Int'l Journal*, *73*(1), 27-35

[4] Baecher, G. B., & Christian, J. T. (2005) Reliability and statistics in geotechnical engineering. *John Wiley & Sons*

[5] Smith, N. J., Merna, T., & Jobling, P. (2014) Managing risk in construction projects. *John Wiley & Sons*

[6] Deng, X., Wang, R., & Xu, T. (2018) Risk assessment of tunnel portals in the construction stage based on fuzzy analytic hierarchy process. *Archives of Civil Engineering*, *64*(4/I), 69-87

[7] Ézsiás, L., Tompa, R., & Fischer, S. (2024) Investigation of the Possible Correlations between Specific Characteristics of Crushed Stone Aggregates. *Spectrum of Mechanical Engineering and Operational Research*, *1*(1), 10-26

[8] Fischer, S. (2025) Investigation of the Settlement Behavior of Ballasted Railway Tracks Due to Dynamic Loading. *Spectrum of Mechanical Engineering and Operational Research*, *2*(1), 24-46

[9] Kong, H. Q., & Zhang, N. (2024) Risk assessment of water inrush accident during tunnel construction based on FAHP-I-TOPSIS. *Journal of Cleaner Production*, *449*, 141744

[10] Koohathongsumrit, N., & Chankham, W. (2024) Risk analysis of underground tunnel construction with tunnel boring machine by using fault tree analysis and fuzzy analytic hierarchy process. *Safety*, *10*(3), 68

[11] Sihombing, O. D. M., Purba, H. H., & Purba, A. (2021) Risk identification in tunnel construction project: A literature review. *Facta Universitatis, Series: Architecture and Civil Engineering*, 261-286

[12] Vitković, N., Marinković, D., Stan, S. D., Simonović, M., Miltenović, A., Tomić, M., & Barać, M. (2024) Decision Support System for Managing Marshalling Yard Deviations. *Acta Polytechnica Hungarica*, *21*(1), 121-134

[13] Hoj, N. (2004) Hazards in tunnels. Structural integrity. In *1st International Symposium "Safe & Reliable Tunnels", Praga* (pp. 4-6)

[14] Jovanovć, V., Janošević, D., Marinković, D., Petrović, N., & Pavlović, J. (2023) Railway load analysis during the operation of an excavator resting on the railway track. *Acta Polytechnica Hungarica*, *20*(1), 79-93

[15] Jovanović, V., Marinković, D., Janošević, D., & Petrović, N. (2023) Influential Factors in the Loading of the Axial Bearing of the Slewing Platform Drive in Hydraulic Excavators. *Tehnički Vjesnik*, *30*(1), 158-168

[16] Eskesen, S. D., Tengborg, P., Kampmann, J., & Veicherts, T. H. (2004) Guidelines for tunnelling risk management: international tunnelling

association, working group No. 2, *Tunnelling and underground space technology*, *19*(3), 217-237

[17] Kazemian, M., Hajimirzajan, A., Ghezelhesar, A. D., Raeisi, E. H., Fischer, S. (2025) Supplementary reference list for Kazemian et al. (2025) entitled Risk Assessment and Response Prioritization for Railway Tunnels Using Integrated Fuzzy FMEA, CRITIC, and Fuzzy MARCOS Methods. https://doi.org/10.13140/RG.2.2.20912.26888

[18] Wang, J. N. (1993) Seismic design of tunnels: a simple state-of-the-art design approach. *Parsons Brinckerhoff*

[19] Hajimirzajan, A., Kazemian, M., & Fischer, S. (2025) A Fuzzy Framework for Assessing and Prioritizing Railway Infrastructure Retrofitting Against Seismic Hazards–A Case Study. Acta Polytechnica Hungarica, *22*(4), 263-283

[20] Federal Highway Administration (2006) Seismic Retrofitting Manual for Highway Structures: Part 1 – Bridges. *U.S. Department of Transportation, Federal Highway Administration*, Report No. FHWA-HRT-06-032

[21] Volkov, V., Taran, I., Volkova, T., Pavlenko, O., & Berezhnaja, N. (2020) Determining the efficient management system for a specialized transport enterprise. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *2024*(4), 185-191

[22] Lv, X., Wang, S., Qiu, Y., & Liu, X. (2021) Study on the Influence of Tectonic Stress on Stability of Horseshoe-Shaped Tunnels. *Advances in Materials Science and Engineering*, *2021*(1), 5566142

[23] Muttil, N., Nasrin, T., & Sharma, A. K. (2023) Impacts of extreme rainfalls on sewer overflows and WSUD-based mitigation strategies: a review. *Water*, *15*(3), 429

[24] Zhou, Y., Liu, M., Zhang, X., Suo, X., & Li, M. (2023) Frost mitigation techniques for tunnels in cold regions: The state of the art and perspectives. *Atmosphere*, *14*(2), 369

[25] Wei, Q., Liu, L., & Wu, C. (2020) A Novel net like structure sensor and gas detection performance in tunnel construction. *Journal of Nanoelectronics and Optoelectronics*, *15*(1), 54-58

[26] Neto, D. C., Chang, H. K., & van Genuchten, M. T. (2016) A mathematical view of water table fluctuations in a shallow aquifer in Brazil. *Groundwater*, *54*(1), 82-91

[27] Lima, S. L., Blackwell, B. F., DeVault, T. L., & Fernández-Juricic, E. (2015) Animal reactions to oncoming vehicles: a conceptual review. *Biological Reviews*, *90*(1), 60-76

[28] Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., Dorren, L. K. A., Gerber, W., & Jaboyedoff, M. (2011) Rockfall

characterisation and structural protection – A review. *Natural Hazards and Earth System Sciences*, *11*(9), 2617-2651

[29] Murphy, M. M., Ellenberger, J. L., Esterhuizen, G. S., & Miller, T. (2016) Analysis of roof and pillar failure associated with weak floor at a limestone mine. *International journal of mining science and technology*, *26*(3), 471-476

[30] Sun, Z., & Akyildiz, I. F. (2011) A mode-based approach for channel modeling in underground tunnels under the impact of vehicular traffic flow. *IEEE transactions on wireless communications*, *10*(10), 3222-3231

[31] Baharun, A. N., Murad, N. A., & Malik, N. N. N. A. (2017) Harmful Gases Profiling in Meru Menora Tunnel using SICK Sensor. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, *15*(2), 888-894

[32] Manley, A. (2009) Security manager's guide to disasters: Managing through emergencies, violence, and other workplace threats. *Security Management*, *53*(7), 44-52

[33] Liu, Y., Apte, V., Luong, Y., Liu, X., & Yung, D. (2007) A methodology for assessment of visibility during road tunnel fires. Journal of fire protection engineering, 17(1), 65-79

[34] Blewett, V., Rainbird, S., Dorrian, J., Paterson, J., & Cattani, M. (2012) Keeping rail on track: preliminary findings on safety culture in Australian rail. *Work*, 41(Supplement 1), 4230-4236

[35] Saukenova, I., Oliskevych, M., Taranic, I., Toktamyssova, A., Aliakbarkyzy, D., & Pelo, R. (2022) Optimization of schedules for early garbage collection and disposal in the megapolis. *Eastern-European Journal of Enterprise Technologies*, *1*(3), 115

[36] Fischer, S., Harangozó, D., Németh, D., Kocsis, B., Sysyn, M., Kurhan, D., & Brautigam, A. (2023) Investigation of heat-affected zones of thermite rail weldings. *Facta Universitatis, Series: Mechanical Engineering, 22*(4), 689-710

[37] Xu, D. S., Zhao, Y. M., Liu, H. B., & Zhu, H. H. (2017) Deformation monitoring of metro tunnel with a new ultrasonic-based system. *Sensors*, *17*(8), 1758

[38] Barone, G., & Frangopol, D. M. (2014) Reliability, risk and lifetime distributions as performance indicators for life-cycle maintenance of deteriorating structures. *Reliability Engineering & System Safety*, *123*, 21-37

[39] Wei, A., & Lu, P. (2022, April) Research on Design of Railway Supervision and Obstacle Removal Special Vehicle Based on Function Analysis Method. In *2022 5th International Conference on Advanced Electronic Materials, Computers and Software Engineering (AEMCSE)* (pp. 34-39) IEEE

[40] Liu, H. C., Liu, L., & Liu, N. (2013) Risk evaluation approaches in failure mode and effects analysis: A literature review. *Expert Systems with Applications*, *40*(2), 828-838

[41] Xiao, N., Huang, H. Z., Li, Y., He, L., & Jin, T. (2011) Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. *Engineering Failure Analysis*, *18*(4), 1162-1170

[42] Stević, Ž., Pamučar, D., Puška, A., & Chatterjee, P. (2020) Sustainable supplier selection in healthcare industries using a new MCDM method: Measurement of alternatives and ranking according to COmpromise solution (MARCOS). *Computers & industrial engineering*, *140*, 106231

[43] Huskanović, E., Stević, Ž., & Simić, S. (2023) Objective-subjective CRITIC-MARCOS model for selection forklift in internal transport technology processes. *Mechatronics and Intelligent Transportation Systems*, *2*(1), 20-31

[44] Koy, A., & Çolak, A. B. (2024) The intraday high-frequency trading with different data ranges: A comparative study with artificial neural network and vector autoregressive models. *Arch. Adv. Eng. Sci.*, *2*(3), 123-133

[45] Marquez, B. Y., Realyvásquez-Vargas, A., Lopez-Esparza, N., & Ramos, C. E. (2024) Application of ordinary least squares regression and neural networks in predicting employee turnover in the industry. *Arch. Adv. Eng. Sci.*, *2*(1), 30-36