A Fuzzy Framework for Assessing and Prioritizing Railway Infrastructure Retrofitting against Seismic Hazards – A Case Study

Amir Hajimirzajan[1], Milad Kazemian[2], Szabolcs Fischer[2]

[1]Department of Industrial Engineering, Yazd University, University Boulevard, Safayieh, Yazd 89195-741, Iran; hajimirzajan@stu.yazd.ac.ir

[2]Department of Transport Infrastructure and Water Resources Engineering Széchenyi István University, Egyetem tér 1, Győr 9026, Hungary
{kazemian.milad,fischersz}@sze.hu

Corresponding author: Szabolcs Fischer

Abstract: The railway system plays a crucial role in a nation's economy and society, extending beyond mere transportation. In earthquake-prone regions like Razavi Khorasan in Iran, railway infrastructure is highly vulnerable to natural disasters, which can severely disrupt train operations. Ensuring the safety of critical infrastructure, including stations, bridges, tunnels, and railway lines, is essential for maintaining operational integrity and public safety. This study evaluates and prioritizes seismic retrofitting measures for railway infrastructures in Razavi Khorasan. The fuzzy Delphi method is used to gather expert opinions, while the Fuzzy VIKOR method facilitates the prioritization process. Key assessment criteria include seismic intensity potential, vulnerability potential of the zone in terms of distance from the fault, the degree of criticality of the infrastructure in terms of the possibility of continuing transportation operations and the current state of the infrastructure in terms of the state of retrofitting against seismic hazards. The findings reveal critical railway segments that require immediate retrofitting interventions and highlight overall vulnerabilities within the system. This paper underscores the effective application of fuzzy logic methodologies in complex decision making scenarios, offering actionable recommendations to enhance the seismic retrofitting of railway infrastructures.

Keywords: Earthquake; Seismic retrofitting; Fuzzy logic; Fuzzy; VIKOR method; Risk assessment; Prioritization

1 Introduction

Urbanization and population growth have increased the need for transportation, making railway transport networks sustainable and effective. Nationwide expansion is crucial for sustainable growth and improving living standards; therefore, examining and assessing every parameter and course of action can be advantageous in addressing environmental and natural challenges [1, 2]. However, earthquakes risk rail infrastructure, leading to long-term blockages and potential social, economic, and security losses. Iran, known for its high seismicity, has a significant railway network in Khorasan Province, situated in regions with moderate, high, and very high seismic risk. However, the railway network within the Khorasan Railway General Directorate's protection zone is crucial for passenger and freight transportation. A system that recognizes, categorizes, and reacts to dangers and issues with a novel and situation-specific solution is needed to evaluate this issue [3]. As a tool for evaluating and prioritizing complex decisions involving ambiguity and uncertainty, fuzzy logic is crucial for quantifying linguistic variables and modeling complex ambiguous and uncertain decisions. This study intends to use fuzzy screening and fuzzy TOPSIS techniques to prioritize seismic retrofitting of railway infrastructure using fuzzy logic. These methods provide a systematic and reliable way to model uncertainties and provide context for decision making based on accurate data. It has been suggested that the streamlined approach to aggregate quality assurance is intended to enhance the resilience and service life of transportation infrastructure, which is the goal of research in this field [4]. When vulnerable infrastructure, such as railroad lines, bridges, tunnels, and stations, is not retrofitted for earthquakes, it results in irreversible financial and human consequences [5, 6]. Significant damage to Turkey's railway infrastructure, estimated at 19.6 million liras, was caused by the recent earthquake that resulted in stone falls on four locomotives and 30 freight wagons [7]. In another example, stopping the train caused a very high financial loss in China's railway network [8]. This article evaluates and prioritizes rail transportation infrastructure in Iran to increase safety, strength, and stability in the face of earthquakes, focusing on strengthening and preventive measures.

2 Literature Review

Seismic hazards threaten railway infrastructure significantly, often resulting in catastrophic consequences .In order to predict future risk patterns and evaluate earthquake risks using various techniques, this section evaluates the research literature on earthquake risks in critical infrastructures, particularly rail transportation. Impact and risk assessment models and technical plans are used in this evaluation [9-11]. Combining 3D fault models with high-quality seismic catalogs creates a reliable seismic risk assessment model crucial for retrofitting structures [12]. In addition, mapping faults using seismic criteria and hierarchical analysis can help identify potential risks for structures, particularly critical facilities [13]. An analysis of the seismic risk in the Tehran Metro area using AHP, Delphi, and literature reviews provides essential information [14]. In another study, the AHP method was used to prioritize risks in Tehran's urban rail transportation networks, identifying earthquakes as a significant priority risk [15]. Whether in railway or other mechanical systems, analyzing loads reveals how various operational conditions can influence performance and highlight potential vulnerabilities. Understanding these factors is essential for effective retrofitting and maintenance strategies in both contexts [16, 17]. Research highlights the importance of risk assessment for rail transportation infrastructure against earthquakes, particularly in the Razavi Khorasan region, using an integrated probabilistic model for multi-hazard seismic risk assessment [18]. Applying the fuzzy technique, the proximity to the fault line, the geological structure, the land slope, the population density of the urban and rural areas, and the distance from communication connections were all valuable elements for creating the vulnerability map [19, 20]. Analyzing and planning for earthquake-related damage in transportation infrastructure is crucial. Simulation and mathematical modeling can examine emergency services feasibility and identify damage reduction strategies [21]. A study assessing seismic vulnerability in railways found that lighter wooden ties create fewer seismic forces than heavy concrete connections, using non-linear springs to represent track and road characteristics [22]. The study evaluates the seismic risk of Ukraine's Lake Baikal railway infrastructure, providing valuable insights for maintenance and repair [23]. A fuzzy assessment model was developed that integrates seismic risk maps and fault data to evaluate earthquake risks. The model uses fuzzy hierarchical analysis to consider geological factors, slope angles, proximity to faults, and road accessibility in risk assessments [24]. In addition, a study uses a fuzzy rule-based model to analyze the influence of geological structures and soil types on building vulnerability during earthquakes, aiding in earthquake risk assessment and mitigation [25]. created a fuzzy evaluation model to evaluate geological features in the South Atlas region of Tunisia, lowering the risk of earthquakes and using fault complexity metrics [26]. Dubnin and Kuksova's study used fuzzy logic methods to assess safety in engineering systems, considering ambiguous factors and interrelationships. They provided a comprehensive risk assessment approach, combining fuzzy sets in a hierarchical cognitive risk model [27]. Assessment of earthquake risk using fault and seismological data has been common in past studies. However, many studies have not explored integrating these evaluations with retrofitting existing infrastructures, particularly in rail transportation, or prioritizing their strengthening. Since evaluation and prioritization rely on expert opinions and considering the uncertainties involved, using fuzzy logic is a practical approach for scientifically addressing the evaluation and prioritization of rail transport infrastructure retrofitting in the Razavi Khorasan region. To address this gap, the authors will explore critical criteria for earthquake risk assessment, methods for selecting important criteria (fuzzy screening), and prioritizing them using fuzzy logic (Fuzzy Delphi and Fuzzy VIKOR). Efficient management systems are vital for improving performance in specialized transport enterprises [28]. Effective management in transport systems contributes to optimizing the performance and productivity of specialized companies, influencing decision making and resource allocation [29].

3 Railway Infrastructure and Seismic Risk

Railway systems are essential for transporting goods and passengers, supporting economies, and maintaining social connectivity. However, in earthquake-prone areas, their structural integrity is often compromised, leading to service disruptions and safety risks. The article emphasizes the need for seismic retrofitting of railway infrastructure, including stations, tunnels, bridges, and blocks, to mitigate earthquake hazards. Different components are vulnerable to various types of seismic damage, such as operational delays, structural failures, and derailments. Documented impacts of seismic activities include economic, social, and security losses due to blocked routes and significant damage from faulting, landslides, or liquefaction. For instance, the Great East Japan Earthquake of 2011 caused significant damage to Japan's high-speed rail network, resulting in widespread disruptions and necessitating extensive repairs [30]. Similarly, the 1999 İzmit earthquake in Turkey severely affected railway lines, causing derailments and structural failures [31]. In recent examples, the structure of railway lines, which consist of pavement and infrastructure, are susceptible to destructive effects from earthquakes, including track buckling, liquefaction, and line subsidence, as seen in New Zealand's 2016 earthquake [32]. In 2022, a 7.3-magnitude earthquake near Fukushima caused a Shinkansen train derailment, while in 2023, a 7.8-magnitude earthquake in Turkey and Syria severely damaged railway lines [33]. Railway lines' vulnerability to earthquakes is influenced by rock falls, landslides, and arc radius. Rockfall intensifies during earthquakes, causing destruction and potential loss of life, especially in blocks with high rock fall amounts [34]. These examples underscore the vulnerability of railway systems to seismic hazards and highlight the need for effective mitigation strategies. Assessing earthquake risks allows for retrofitting railway stations and structures, enhancing resilience through periodic evaluations and modifications. Landslides triggered by earthquakes can significantly damage railway lines. Given the critical importance of railway infrastructure and its vulnerability to seismic hazards, it is essential to implement effective measures for seismic risk assessment and mitigation. This research aims to evaluate the potential effects of seismic hazards on railway infrastructure, explicitly focusing on stations, railway tunnels, bridges, and blocks. Figure 1 shows the proposed fuzzy framework for evaluating railway infrastructure against seismic hazards and prioritizing their retrofitting plan.

Based on this, First, based on seismic, geographical data, and infrastructure retrofitting assessment, a list of the most essential criteria is identified. Initial assessment criteria include the following:

- seismic activity potential,
- zone vulnerability based on proximity to fault lines,
- infrastructure criticality regarding operational continuity during earthquakes,

- crisis recovery capabilities,
- current retrofitting status of infrastructure against seismic risks,
- proximity to the nearest supporting railway station.

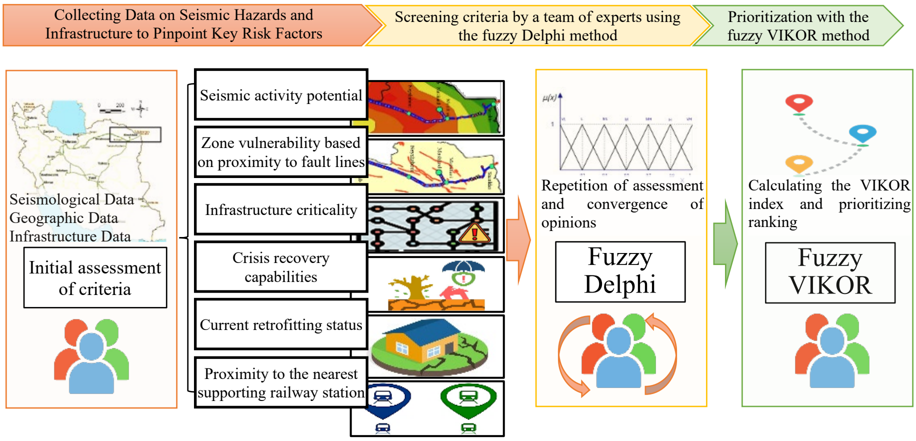

Figure 1

A proposed fuzzy framework for evaluating railway infrastructure and prioritizing retrofitting against seismic hazards

Then, the proposed framework employs qualitative assessment methods, including expert opinion elicitation through the Fuzzy-Delphi method, for screening criteria and assessing the vulnerability of different railway components to seismic events. Then, it uses the Fuzzy-VIKOR method to prioritize retrofitting railway infrastructure. In the following, while further explaining the mentioned framework by using it in a case study to evaluate and prioritize the retrofitting of the Khorasan Railway Directorate of Iran's railway infrastructure, this study shows the effectiveness of the proposed framework.

4 Measuring and Prioritizing the Seismic Retrofitting of Railway Infrastructure in the Khorasan Railway Directorate

Iranian Khorasan Railway provides passenger and freight services between Mashhad and Neqab, reaching the Turkmenistan border and Fariman to Sarakhs. This study employs the fuzzy screening method to evaluate and prioritize seismic risks associated with the Khorasan Railway infrastructure, as shown in Figure 2 shows 23 stations, three tunnels, and several bridges. There are several initial criteria to determine the priority for retrofitting buildings: seismic intensity potential, vulnerability potential of the zone in terms of distance from the fault, the degree of criticality of the infrastructure in terms of the possibility of continuing transportation operations in earthquake conditions, recovery potential in crises, the current state of the infrastructure in terms of the state of retrofitting against seismic hazards and finally distance from the nearest supporting railway station. Expert opinions guide the evaluation of these criteria to determine the priority for retrofitting buildings.

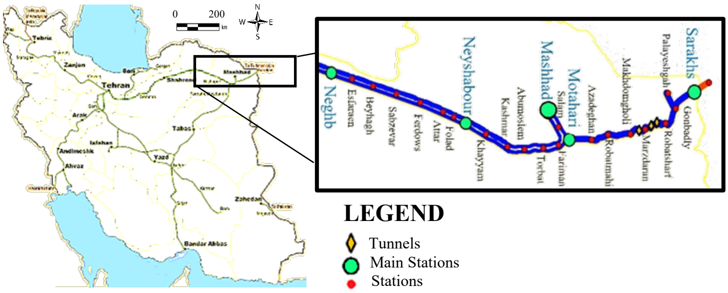

Figure 2

General Administration of Khorasan Railway in Iran

4.1 Evaluate and Screen the Primary Criteria using the Fuzzy Delphi Approach

This section uses the fuzzy Delphi [35] approach to evaluate and screen the primary criteria [36]. The fuzzy Delphi method was introduced by Kaufman and Gupta in 1988 and proposed by Ishikawa et al. [37]. So, this section emphasizes the Fuzzy Delphi process for identifying critical criteria in assessing and screening earthquakes and seismic vulnerability, and then this study uses Fuzzy VIKOR for prioritizing retrofitting infrastructure against seismic hazards. In other words, the study employs the Fuzzy Delphi method to identify relevant criteria, followed by the Fuzzy VIKOR approach to rank railway infrastructure priority for retrofitting in Khorasan. The Delphi method is recognized as effective for qualitative assessments, fostering expert consensus through Linguistic variables and repeated evaluations for informed management decisions. The steps to implement this method are explained as follows. As a first step, an expert team with adequate knowledge and experience in seismic hazards must be formed to assess earthquake and seismic risks on railway infrastructure.

Table 1

Linguistic scales for expert team judgment

Abbreviation	Linguistic variables	Triangular Fuzzy numbers
VL	Very Low	(0.00,0.00,1.00)
L	Low	(0.00,0.10,0.30)
ML	Medium Low	(0.10,0.30,0.50)
M	Medium	(0.30,0.50,0.70)
MH	Medium High	(0.50,0.70,0.90)

H	High	(0.70,0.90,1.00)
VH	Very High	(0.90,1.00,1.00)

These experts should understand the destructive impact of earthquakes and seismic on railway operations and associated risks. The study refers to these experts as "EX." Choosing team members with a successful railway construction and maintenance background is essential. The study acknowledges that expertise varies among team members and assigns weights to their opinions, using triangular fuzzy numbers to quantify their expertise. In the second step, expert team members evaluate the importance of retrofitting criteria using appropriate linguistic terms. These linguistic variables are converted into triangular fuzzy numbers with membership degree $\mu(x)$ to minimize personal bias. The study defines these variables according to specified triangular fuzzy numbers, as presented in Table 1 and illustrated in Figure 3.

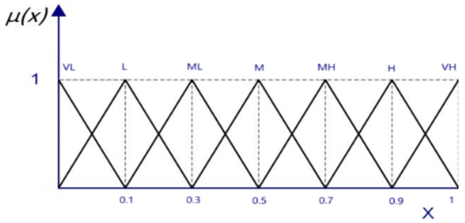

Figure 3

Display of triangular fuzzy numbers equivalent to each of the linguistic variables in Table 1

After completing the questionnaire by the expert members (EX), collect the criteria and convert the results into triangular fuzzy numbers in the form of the matrix as equation 1.

$$\widetilde{W}_k = \begin{array}{cc} & \begin{array}{ccc} EX_1 & \cdots & EX_k \end{array} \\ \begin{array}{c} C_1 \\ \vdots \\ C_i \end{array} & \begin{bmatrix} \widetilde{w}_1^1 & \cdots & \widetilde{w}_1^k \\ \vdots & \ddots & \vdots \\ \widetilde{w}_i^1 & \cdots & \widetilde{w}_i^k \end{bmatrix} \end{array}, (i = 1,2,\dots,m; k = 1,2,\dots,p) \tag{1}$$

where $\widetilde{W}_k$ is the expert's judgment matrix about the importance of the weight of the retrofitting criteria, C_i is the i-th criterion of the expert's EX_k and $\widetilde{w}_i^k$ is the triangular fuzzy number corresponding to the linguistic evaluation of the expert k about the importance of the weight of the i-th criterion, the mean. The weight of each criterion can be determined using equation 2.

$$\widetilde{W}_i = \frac{\sum_{k=1}^{p} \tilde{r}_k \otimes \widetilde{w}_i^k}{\sum_{k=1}^{p} \tilde{r}_k}, \forall i = 1,2,\dots,m \tag{2}$$

where $\widetilde{W}_i$ is the average weight of criterion i and $\widetilde{w}_i^k$ is the triangular fuzzy number corresponding to the importance of the weight assigned by EX_k to criterion i and $\tilde{r}_k$ is the weight of EX_k.In the third step, screening the appropriate criteria, among the existing criteria, the most important ones should be identified to maintain rail transport's stability. In this way, the criteria not significantly compatible with the retrofitting and stability of rail transport are removed. The criteria and appropriate measures will be finalized to prioritize infrastructure after creating an agreement between the expert team and the convergence of opinions. For this purpose and also to speed up the convergence process of expert team opinions, define an index called minimum acceptable weight $\widetilde{W}_\delta$. Identification of inappropriate criteria is done by comparing the weight of the criteria $\widetilde{W}_i$ with this index $\widetilde{W}_\delta$. Based on if $\widetilde{W}_i \geq \widetilde{W}_\delta$, the proportional criterion is recognized, and otherwise, it is removed. The $\widetilde{W}_\delta$ index is calculated as equation 3.

$$\widetilde{W}_\delta = \frac{\sum_{k=1}^{p} \tilde{r}_k \otimes \widetilde{w}_\delta^k}{\sum_{k=1}^{p} \tilde{r}_k} \tag{3}$$

where $\widetilde{w}_\delta^k$ is the minimum acceptable weight for criteria in terms of $EX_k$and $\tilde{r}_k$ is the weight of EX_k. After performing these comparisons, if a criterion is removed, this study has to repeat the steps related to completing the questionnaire described in the previous step due to the lack of convergence of the opinions of the expert team. (Completing the new questionnaire according to the remaining criteria) The condition for identifying appropriate criteria (end of comparisons and converging opinions of the expert team) and entering into the next step is not to remove any of the prioritization criteria in the comparison stage. In order to speed up the creation of convergence between experts' opinions, the results of the questionnaire of the previous steps can be presented to each expert team member.

In the fourth step, this study calculates the criteria's normal weight. After converging the expert team's opinions and identifying the appropriate criteria to maintain the stability of rail transportation infrastructure during an earthquake, the average weight calculated from the evaluation of the last questionnaire is considered as the weight of the proportional merit criteria. Since all the criteria in the merit model are profit criteria ($C_i \in B$), using the normalization rules of triangular fuzzy numbers, this study calculate the fuzzy normal weight of each criterion in eq. 4.

$$\widetilde{W}'_i = \left(\frac{w_i^l}{\max\limits_j w_i^u}, \frac{w_i^m}{\max\limits_j w_i^u}, \frac{w_i^u}{\max\limits_j w_i^u} \right) \tag{4}$$

where $\widetilde{W}'_i = \left(w'^l_i, w'^m_i, w'^u_i\right)$ x is the fuzzy normal weight of criterion i and w'^l_i ،w'^m_i، w'^u_i are the lower, middle, and upper bounds of fuzzy weight $\widetilde{W}'_i$, respectively. After determining $\widetilde{W}'_i$, the normal weight of criteria whose definitive value is W'_i is calculated based on equation 5.

$$W'_i = \frac{w'^l_i + 4w'^m_i + w'^u_i}{6} \tag{5}$$

where W'_i is the normal weight of criterion i. A normalization decision matrix would be formed in the last step of fuzzy Delphi screening. At this stage, the normal fuzzy decision of the problem is formed to enter the matrix fuzzy-VIKOR process.

For this purpose, each expert team member evaluates the necessity of retrofitting each infrastructure by selecting the appropriate linguistic variable in Table 1. After obtaining the score for each infrastructure, the average score for all criteria is calculated with the help of equation 6.

$$\tilde{X}_{ij} = \frac{\sum_{k=1}^{p}(\tilde{r}_k \otimes \tilde{x}_{ij}^{k})}{\sum_{k=1}^{p}\tilde{r}_k} \quad (\forall i = 1,2,\dots,m, \qquad j = 1,2,\dots n) \tag{6}$$

where $\tilde{X}_{ij}$ is the final score of the need to retrofit infrastructure j in accordance with criterion i, and $\tilde{r}_k$is the weight and EX_k, and $\tilde{x}_{ij}^{k}$is the performance of infrastructure jth in criterion i th according to the linguistic evaluation of EX_kTherefore, considering that all the criteria are from profit (positive effect), the procedure forms the fuzzy normal decision matrix in equation 7.

$$\widetilde{D} = \begin{array}{c c} & \begin{array}{ccc} M_1 & \cdots & M_n \end{array} \\ \begin{array}{c} C_1 \\ \vdots \\ C_m \end{array} & \begin{bmatrix} \widetilde{X}'_{11} & \cdots & \widetilde{X}'_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{X}'_{m1} & \cdots & \widetilde{X}'_{mn} \end{bmatrix} \end{array} \tag{7}$$

that $\tilde{X}'_{ij} = \left(\frac{x_{ij}^{l}}{\max_j x_{ij}^{u}}, \frac{x_{ij}^{m}}{\max_j x_{ij}^{u}}, \frac{x_{ij}^{u}}{\max_j x_{ij}^{u}}\right)$ is the normal value of $\tilde{X}_{ij}$, $C_i(i = 1,2,\dots,m)$ is the i criterion and M_j $(j - 1,2,\dots n)$ is the jth option. Also, according to equation 8, W'_i is the normal weight of criterion i.

$$W'_i = \{W'_1, W'_2, \dots, W'_m\} \tag{8}$$

4.2 Determining Priorities with the Fuzzy-VIKOR Approach

VIKOR method is a multi-criteria decision making (MCDM) method developed by Serafim Opricovic in 1979 based on the LP metric method to solve decision problems [38]. This method's criteria for ranking options are based on how close they are to the ideal answer [39]. The reason for using the VIKOR method in the proposed combined method is that the characteristics and capabilities of this method can choose the infrastructure closer to the ideal answer than others. In practice, this method can help to choose the most important and key infrastructure for retrofitting, which is closer to the ideal solution and has maximum group utility and minimum individual impression. The steps of the fuzzy VIKOR process related to the presented hybrid model are described below. In the first step, According to the formation of the fuzzy normal decision matrix $\widetilde{D}$, in the final step of the fuzzy Delphi method, the study determines the best fuzzy value ($\tilde{F}_i^{*}, FBV$) and the worst fuzzy value ($\tilde{F}_i^{-}, FWV$) of each criterion using equation 9.

$$\tilde{F}_i^{*} = \max_j \tilde{X}'_{ij}\,; \tilde{F}_i^{-} = \min_j \tilde{X}'_{ij} \quad (\forall i = 1,2,\dots,m, j = 1,2,\dots n) \tag{9}$$

In the second step, using relations 10 and 11 respectively, first, the values of $S_j$and R_j are calculated.

$$S_j = \sum_{i=1}^{m} W'_i \frac{D(\tilde{F}_i^*, \tilde{X}'_{ij})}{D(\tilde{F}_i^*, \tilde{F}_i^-)} \tag{10}$$

where S_j is the utility measure of infrastructure jth, $D(\tilde{F}_i^*, \tilde{X}'_{ij})$ represents the distance of options $(\tilde{X}'_{ij})$ from the best fuzzy value $(\tilde{F}_i^*)$ and $D(\tilde{F}_i^*, \tilde{F}_i^-)$also show that the distance between the best $(\tilde{F}_i^*)$ and the worst $(\tilde{F}_i^-)$ is a fuzzy value, and the framework evaluates R_j using equation 12.

$$R_j = \max_i \left[W'_i \frac{D(\tilde{F}_i^*, \tilde{X}'_{ij})}{D(\tilde{F}_i^*, \tilde{F}_i^-)} \right] \tag{11}$$

where R_j represents the impression size of infrastructure jth. After calculating the S_j and R_j values for the final ranking, the proposed framework calculates the Q_j index for all options using equation 12.

$$Q_j = \nu \left[\frac{(S_j - S^-)}{(S^* - S^-)} \right] + (1 - \nu) \left[\frac{(R_j - R^-)}{(R^* - R^-)} \right] \tag{12}$$

That $S^* = \max_j S_j$؛ $S^- = \min_j S_j$, $R^* = \max_j R_j$, $R^- = \min_j R_j$, are Q_j is the VIKOR index and expresses the VIKOR value of the jth infrastructure. ν is also a weight for the group's maximum utility strategy, which can have a value between 0 and 1, but is usually considered equal to 0.5 in calculations. As the final step to rank the options, the proposed framework arranges the values of S_j, R_j and Q_j in descending order, which results in three ranking modes to identify infrastructure retrofitting priorities. According to VIKOR 's method, the option with the lowest value of $Q_j$will be the most important priority. Since the proposed framework is looking to find a group of the most important infrastructures in this study, the framework is looking for a set of key compromise solutions. Because an infrastructure may have a high rank in S or R, and therefore, to find a compromise in the sustainable decision making process, the value of parameter ν can be adjusted. If ν>0.5, then more group favorability is obtained, and in case of general agreement or disagreement, the values are selected as $\nu \approx 0.5$ and $\nu < 0.5$. Considering the value of the parameter ν, n options, including $A_1, A_2, \ldots, A_n$that apply to the following relation 13 can be selected as the set of the most important priorities for retrofitting infrastructures.

$$Q(A_n) - Q(A_{n-1}) \geq \frac{1}{n-1} \tag{13}$$

5 Introduction of Retrofitting Prioritization Criteria within the Scope of Khorasan Railway General Administration

5.1 Seismic Activity Potential

Potential Seismic activity measures the effects of an earthquake at specific locations, reflecting the severity of ground shaking and its impact on structures and the environment. A seismic hazard map in Iran has been developed to facilitate risk analysis, as shown in Figure 4 [40]. This map incorporates updated seismic data, including a comprehensive seismic catalog and new tectonic models for the 475-year return period. The map provides crucial information about key infrastructures, allowing for a better understanding of the seismic risks they face. The updated hazards map aims to assist in effective seismic hazard management and mitigation strategies across the region by calculating seismic parameters and using probabilistic methods. Seismic hazard for PGA values is between 0.05 and 0.14 very low, between 0.15 and 0.22 low, between 0.23 and 0.28 moderate to low, between 0.29 and 0.34 moderate, between 0.35 and 0.39 moderate to high, between 0.40 and 0.45 high, and between 0.46 and 0. Up to 0.50 is considered too high.

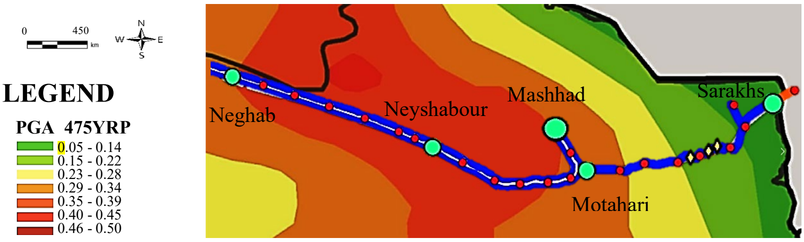

Figure 4
Semiteic hazard map in the area of Khorasan Railway General Administration

The evaluation of this criterion can play a key role in identifying the most critical infrastructures for strengthening against seismic hazards. The higher the risks in the area where the railway infrastructure is located, the greater the risk of risks and the need for retrofitting.

5.2 Zone Vulnerability based on Proximity to Fault Lines

Distance from fault lines is one of the most critical indicators of seismic and earthquake vulnerability. A distance of less than 1 km to fault lines is considered a zone with very high vulnerability; a distance of 1 to 30 km is regarded as a zone with high vulnerability; a distance of 30 to 50 km is considered a zone with medium vulnerability; and a distance of more than 50 km is regarded as a zone with low vulnerability. The zoning of the distance from the fault lines in the area of the Kharsan Railway Directorate is shown in Figure 5.

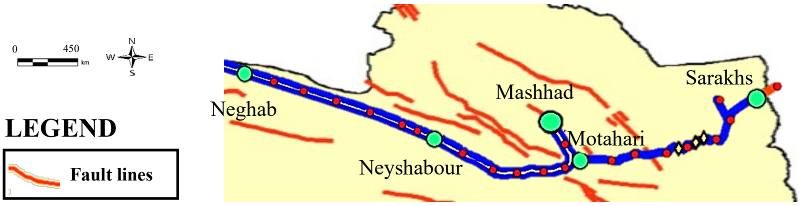

Figure 5
Zoning the distance from the fault lines in the scope of Khorasan Railway General Administration

5.3 Infrastructure Criticality regarding Operational Continuity during Earthquakes

The value of this criterion shows the effect that possible seismic and earthquake hazards will have on rail transportation operations, taking into account the economic and social consequences caused by the railway system's cessation of transport services. Considering the greater importance of passenger rail transportation, all related infrastructures are more critical. In general, the route from Mashhad to Neqhab is generally a passenger rail transport route (Mashhad-Tehran rail route), and the Sarakhs-Kashmer route (part of the Sarakhs-Bandar Abbas rail transit route) is a cargo rail transport route. In the meantime, the Fariman-Kashmer rail route is of particular importance with the simultaneous use of cargo and passengers. This criterion is low for the Salam-Motahari block and the blocks between Motahari station and Sarakhas station, where most of the trains are cargo trains; for the Mashhad-Salam and Salam-Fariman blocks and blocks between Kashmar station and Neqhab station, due to the presence of passenger trains, this criterion is medium and high. The blocks between Fariman station and Kashmar station are considered high due to the presence of passenger and freight trains.

5.4 Crisis Recovery Capabilities

This criterion specifies the recovery potential in times of crisis regarding the amount of power and relief equipment needed for infrastructure reconstruction. The higher the value of this measure is, the faster it will be possible to respond to seismic hazards and earthquakes.

5.5 Current Retrofitting Status of Infrastructure against Seismic Risks

The current condition (before the earthquake) of each of the investigated blocks, stations, bridges, and tunnels was studied as one of the parameters affecting the vulnerability caused by the possible earthquake.

5.6 Proximity to the Nearest Supporting Railway Station

This defining criterion is similar to criterion 5.4, which shows the distance of each infrastructure to the main stations with support facilities. The longer this distance, the greater the recovery potential in times of crisis in terms of providing power and support equipment for infrastructure reconstruction.

6 Prioritization of Retrofitting of Railway Infrastructure using the Fuzzy Delphi and Fuzzy VIKOR Method

In this section, the proposed framework evaluates the most important criteria of vulnerability against seismic hazards by using the fuzzy Delphi technique and fuzzy VIKOR. Then, by evaluating the existing infrastructure with the identified criteria, the proposed framework will determine the infrastructure priority for retrofitting the rail transport infrastructure, including rail lines (rail blocks), bridges, tunnels, and stations in the Khorasan railway region. In order to evaluate the criteria, First of all, it is necessary to specify the expert team. For this purpose, in the proposed framework, the expert team selected included six managers of the Khorasan railway region with appropriate experience and knowledge in developing and maintaining railway infrastructure. This team consists of six experienced experts, including the general manager, the technical and infrastructure deputy, the operation deputy, the head of the line and technical structures department, the head of the construction and facilities department, and an expert with line and construction experience in the general department. Khorasan Railway brings a wealth of knowledge and insight into the evaluation process.

According to the work experience, three people with weight (1, 2, 2), two people with weight (0.5, 1, 1.5), and one person with weight (0, 0, 1) according to the method mentioned in the previous section. As members of the expert team, they evaluate the criteria. The choice of criteria is an essential and key factor in achieving the goals of this study. Each choice between different criteria creates different evaluation results. As a result, the appropriate selection of criteria is important. The fuzzy Delphi method is used to evaluate and select the criteria with the most desirability, which adds to the richness of the research. The primary purpose of this method is to screen criteria or indicators from the perspective of a team of experts in a specialized subject. In other words, the Delphi method is an approach to building consensus on issues whose objectives and components are not clearly defined. Considering that experts' evaluations are based on experience and expertise, it is better. Using fuzzy numbers in evaluation is much better than using definite numbers. The fuzzy Delphi method works better by integrating the Delphi method and fuzzy theory, which was introduced in the previous section.

A questionnaire was prepared to determine the average weight of each criterion, and all members were asked to evaluate the importance of each criterion by choosing the appropriate word from the seven linguistic words in Figure 1. In this research, six infrastructure evaluation criteria include seismic intensity potential, vulnerability potential of the zone in terms of distance from the fault, the degree of criticality of the infrastructure in terms of the possibility of continuing transportation operations in earthquake conditions, recovery potential in crises, the current state of the infrastructure in terms of the state of retrofitting against seismic hazards and distance from the nearest railway stations with recovery facilities. In order to identify appropriate criteria, each analyst specified his minimum acceptable weight ($\widetilde{w}_\delta^k$). Based on this, if a criterion does not meet the condition of the fuzzy relationship $\widetilde{w}_i > \widetilde{w}_\delta^k$, it is identified as an inappropriate criterion and removed from consideration. At this stage, the initial selection criteria are seismic intensity potential, vulnerability potential of the zone in terms of distance from the fault, the degree of criticality of the infrastructure in terms of the possibility of continuing transportation operations in earthquake conditions, recovery potential in crises, the current state of the infrastructure in terms of the state of retrofitting against seismic hazards and distance from the nearest railway stations with recovery facilities. By setting up the second questionnaire, the remaining criteria were re-evaluated. The expert team distributed the analyzed results to speed up the convergence process and increase the consensus probability. The results showed that the average evaluation weights of all criteria are greater than the value of $\widetilde{w}_\delta$. Table 2 shows the value of the best and the worst value of the fuzzy value of evaluation criteria ($\widetilde{F}_i^-$, $\widetilde{F}_i^*$) for prioritization of railway infrastructure in Khorasan.

Table 2

The best and worst fuzzy values of evaluation criteria for prioritization of railway infrastructures in Khorasan

Criteria	$\widetilde{\boldsymbol{F}}_i^-$	$\widetilde{\boldsymbol{F}}_i^*$
Seismic activity potential	(0.16,0.40,0.96)	(0.09,0.13,0.73)
Zone vulnerability based on proximity to fault lines	(0.09,0.18,0.72)	(0.20,0.41,0.99)
Infrastructure criticality regarding operational continuity during earthquakes	(0.06,0.21,0.66)	(0.18,0.45,1.00)
Current retrofitting status of infrastructure against seismic risks	(0.08,0.23,0.63)	(0.13,0.37,0.91)

So, as a result, the convergence between the expert team has been. Next, the remaining criteria were calculated with the help of the mentioned criteria, and then, to form the normal fuzzy matrix, the expert team was asked to evaluate the current state of the infrastructure in terms of the risk of earthquake hazards with the help of linguistic variables. The results of this evaluation can be seen in Table 2. As can be seen, these infrastructures include 24 blocks, three tunnels, five bridges, and five stations. Finally, to rank the infrastructures, the values of S_j, $R_j$and Q_j were calculated, and the results can be seen in Tables 3 to 6.

To visually represent the intensity of risk or effects, a color spectrum has been used that shows differences based on intensity levels. Intensities tending toward green indicate lower priority for infrastructure for remediation, while colors tending toward red indicate higher priority. This color spectrum helps users quickly identify infrastructure with the highest or lowest risk, allowing for an accurate assessment of the condition of the infrastructure.

Table 3

The final table of the risk rating of Seismic hazards in the railway infrastructure of the Khorasan Railway Administration (Blocks)

	The Blocks to be evaluated/prioritized	S_j	R_j	Q_j
Blocks	Mashhad - Salam	2.40	0.17	0.34
	Salam - Fariman	2.20	0.16	0.24
	Fariman - Torbat	2.03	0.15	0.18
	Torbat - Abu Muslem	1.62	0.12	0.00
	Abu Muslem - Kashmar	1.81	0.13	0.08
	Kashmar - Khayam	2.22	0.16	0.26
	Khayam - Neishabour	2.25	0.16	0.27
	Neishabour - Fulad	2.25	0.16	0.26
	Fulad - Attar	2.23	0.16	0.26
	Attar - Ferdows	2.23	0.16	0.27
	Ferdows - Sabzevar	2.25	0.16	0.27
	Sabzevar - Beyhaq	2.28	0.16	0.27
	Beyhaq - Esfarayen	2.25	0.16	0.26
	Esfarayen - Niqab	2.81	0.20	0.51
	Salam - Motahari	2.39	0.17	0.32
	Fariman - Motahari	2.63	0.19	0.44
	Motahari - Azadegan	3.19	0.23	0.67
	Azadegan - Robat Mahi	2.78	0.20	0.50
	Robat Mahi - Makhtum Qoli	3.03	0.22	0.61
	Makhtum Qoli - Marzdaran	3.56	0.25	0.82
	Marzdaran - Robat Sharif	3.93	0.29	1.00
	Robat Sharof - Gonbadli	3.92	0.28	0.96
	Gonbadli - Sarakhs	3.70	0.26	0.88
	Sarakhs - Tajan	3.74	0.27	0.91

Table 4

The final table of the risk rating of earthquake hazards in the railway infrastructure of the Khorasan Railway Administration (Tunnels)

	The Tunnels to be evaluated/prioritization	S_j	R_j	Q_j
Tunnels	km 971+460 to 973+740	3.44	0.25	0.78
	km 982+320 to 984+920	3.52	0.25	0.81
	km 985+740 to 986+780	3.50	0.25	0.81

Table 5
The final table of the risk rating of earthquake hazards in the railway infrastructure of the Khorasan Railway Administration (Important Bridges)

The bridges to be evaluated/prioritization		S_j	R_j	Q_j
Important bridges	Eleven Cheshme Bridge (km 911+016)	3.47	0.26	0.78
	Tajan Bridge (1052+837)	4.05	0.30	1.04
	Kanivo Bridge (km 994+308)	3.90	0.28	0.96
	Attar Bridge (km 761+928)	2.07	0.15	0.16
	Motahari Bridge (km 890+687)	2.91	0.21	0.52

Table 6
The final table of the risk rating of earthquake hazards in the railway infrastructure of the Khorasan Railway Administration (Important Bridges)

The stations to be evaluated/prioritization		S_j	R_j	Q_j
Important stations	Mashhad station	2.64	0.19	0.42
	Neishabour station	2.07	0.15	0.16
	Niqab station	2.84	0.20	0.49
	Motahari station	2.08	0.15	0.17
	Sarakhs station	3.53	0.25	0.78

The results show that the most critical blocks are between Fariman and Kashmar, including the Torbat-Abu Muslem, Abu Muslem-Kashmar, and Fariman-Torbat blocks. The analysis reveals that the blocks between Fariman and Kashmar, particularly the Torbat-Abu Muslem block with a VIKOR factor of 0.0, the Abu Muslem-Kashmar block with a proximity factor of 0.08, and the Fariman-Torbat block with a VIKOR factor of 0.18, are the most vulnerable and should be prioritized for retrofitting. Additionally, the railway axis from Motahari station to Mashhad and from Mashhad to Niqab, which scored VIKOR factors of 0.00 and 0.51, respectively, also demand immediate seismic strengthening. In contrast, the blocks between Motahari station and Sarkhes, especially the Marzdaran-Rabat Sharaf block (VIKOR factor 1.0), have the lowest priority for retrofitting. The most critical block of this rail route is the Salam-Motahari block (VIKOR factor 0.32). Generally, as you can see, the rail route in Salam-Serkhes is much safer against seismic hazards. For the tunnels, the tunnel in km 971+460 to 973+740 with a VIKOR value of 0.78 has the highest priority for strengthening the infrastructure against seismic hazards. The other two investigated tunnels with a VIKOR value of 0.81 have the same priority for retrofitting. So, among the critical bridges, the Attar Bridge, with a VIKOR factor of 0.16, and the Motahari Bridge, with a VIKOR factor of 0.52, require significant retrofitting efforts to enhance their earthquake resilience. Regarding railway stations, the Neishabur and Shahid Motahari stations are the most critical, each with a VIKOR factor of 0.16 and 0.17, followed by Mashhad station with a VIKOR factor of 0.72 and Niqab station with a VIKOR factor of 0.49. These stations should be prioritized for seismic retrofitting to mitigate the potential risks of seismic events.

Conclusions

This article discusses assessing and prioritizing railway infrastructure retrofitting against seismic hazards with the fuzzy logic framework. In order to show the effectiveness of the presented fuzzy framework, this study examined the results of the evaluation analysis performed in a case study of the Khorasan Railway General Administration. The fuzzy logic approach was chosen because of its high capability in managing uncertainties and complexities in the evaluation and decision making process. This method enables more accurate and realistic analysis by combining quantitative evaluation and converting them into fuzzy values. Based on the results of this study, Blocks between Fariman and Kashmar, in particular the blocks Torbat-Abu Muslim with VIKOR factors of 0.0 and Abu Muslem-Kashmar blocks with proximity factors of 0.08 and 0.18, are the most vulnerable and need to be retrofitted the most. Motahari station to Mashhad and Mashhad to Niqab railway axes, with VIKOR factors of 0.00 and 0.51, also require immediate seismic reinforcement. As a result, the blocks between Motahari and Sarkhes have the lowest retrofitting priority, especially the Marzdaran-Rabat Sharaf blocks (VIKOR factor 1.0). This rail route has a very safe seismic route in Salam-Serkhes due to the VIKOR factor of 0.32. Among the tunnels, the tunnel in km 971+460 to 973+740 with a VIKOR value of 0.78 has the highest priority for seismic strengthening. Both tunnels with VIKOR values of 0.81 also require retrofitting. Thus, among critical bridges, the Attar Bridge, with a VIKOR factor of 0.16, and the Motahari Bridge, with a VIKOR factor of 0.52, require significant retrofitting. Finally, Among railway stations, Neishabur and Shahid Motahari are the most critical, with VIKOR factors of 0.16 and 0.17, followed by Mashhad, with a VIKOR factor of 0.72, and Neqhab, with a VIKOR factor of 0.49. Investing in these stations will mitigate seismic risks. This article uses a fuzzy logic framework to explore the assessment and prioritization of railway infrastructure retrofitting against seismic hazards. The study applies the framework to a Khorasan Railway General Administration case study. Using Fuzzy Delphi and Fuzzy VIKOR methods, the research identifies the most critical railway segments needing urgent attention. Fuzzy logic is employed for its ability to handle uncertainties and complexities in evaluation and decision making. This approach allows for more accurate and realistic analysis by converting quantitative evaluations into fuzzy values. The study emphasizes the pressing need for seismic retrofitting in priority areas to mitigate earthquake damage and protect the rail network and its freight and passengers. Future research in this area could expand on the integration of the effects of other natural hazards or the exploitation of seismic monitoring system data and community-based risk perception for a more accurate and shorter-term assessment of seismic hazards and, ideally, the integration of a possible redistribution of seismic events due to climate changes. Future research could also integrate machine learning and neural network methods into the proposed fuzzy framework presented in this study.

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