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ORIGINAL PAPER

A novel seismic vulnerability assessment for the urban roadway by using interval valued fermatean fuzzy analytical hierarchy process

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Abstract
Seismic activity poses significant challenges to urban road infrastructure, often resulting in road closures due to the combined effects of damaged buildings and affected road networks. In contrast, the resilience of roads is crucially important for all kinds of relief activities after an earthquake in this context, this study outlines a methodological framework for assessing the vulnerability of urban road infrastructure to seismic activity. By integrating various criteria within an Interval-valued Fermatean fuzzy Analytic Hierarchy Process framework, the approach offers a comprehensive analysis of vulnerability, considering both quantitative and qualitative factors. This method is a weighting method that has not been used before in MCDM studies in the field of earthquakes. A risk factor is obtained for each road section by using this comprehensive analysis of the vulnerability. This integrated approach considers the interplay between damaged buildings, road networks, and disaster response mechanisms, thereby enhancing the ability to anticipate and respond to seismic events effectively. The study conducts a case study in Istanbul, Turkey, a seismic-prone area, to validate the effectiveness of the proposed methodology. Key findings indicate that the approach can identify and quantify vulnerabilities within the transport network, enabling the identification of high-risk areas for necessary mitigation measures. Moreover, the methodology's validity is confirmed through a validation study in Gölbaşı district, Adıyaman, Türkiye, which experienced severe damage during earthquakes on 6 February 2023 earthquakes. By providing a structured and comprehensive vulnerability analysis, the research aims to contribute to the resilience of urban infrastructure, particularly in earthquake-prone regions.

Keywords Vulnerability index · Urban roads · Interval valued fermatean fuzzy analytical hierarchy process · Road infrastructures · Road risk assessment · Earthquake-induced road damage

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1 Introduction

The critical role of infrastructure, particularly transport systems, in ensuring national security and facilitating economic and social prosperity is well known. Transport systems are critical infrastructures ensuring national security during and/or after natural disasters and the recovery phase. Vulnerability of transport systems, especially roadways, to earthquakes, which can lead to extensive damage, economic losses, and hindrances to emergency response efforts, is a critical issue in earthquake preparedness. Furthermore, this destruction affects tourism, trade, and/or other industries, resulting in long-term and indirect economic losses (El-Maissi et al. 2020). As shown in Fig. 1, seismic events historically have caused severe damage to buildings and infrastructure systems such as roadways (Anbazhagan et al. 2012; Brabhaharan 2006; Maruyama et al. 2010). In this context, a systematic approach is needed to assess, prioritize, and manage risks in road networks (Brabhaharan 2006). The most important of these approaches is seismic vulnerability assessment, which can be defined as the sensitivity of road networks to events (Berdica 2002).

The vulnerability approach for roadway systems can be divided into two groups: physical and traffic-based, as shown in Fig. 2. Physical approaches consist of fragility curves (Argyroudis et al. 2019; Argyroudis and Kaynia 2015; Maruyama et al. 2010) and vulnerability index (VI) (Adafer and Bensaibi 2017; Cirianni et al. 2008; D'Andrea et al. 2005; Francini et al. 2020). On the other hand, traffic-based approaches consist of accessibility analysis (Chang 2003; Delamater et al. 2012; D'este and Taylor 2003; Ertugay and Duzgun 2011; Yang et al. 2006) and link importance index (Balijepalli and Oppong 2014; Jenelius et al. 2006; Nagurney and Qiang 2007; Scott et al. 2006; Taylor et al. 2006; Zhang et al. 2020). Of all these vulnerability assessments, the Vulnerability Index (VI) approach is

Fig. 1 **(a)** Damage to road in 1931 Napier Earthquake (Brabhaharan 2006) **(b)** Damage of road due to Muzaffarabad earthquake (Peiris and Free 2006) **(c)** Pan-American Highway damage near the Pacific Ocean due to Peru earthquake (O'Connor et al. 2007) **(d)** Road damage in Yingxiu due to Wenchuan earthquake (Zifa 2008) **(e)** Damaged road due to Christchurch earthquake (Anbazhagan et al. 2012) **(f)** Damage of bridge approach road due to Myanmar (Burma) earthquake 2001 (Anbazhagan et al. 2012)

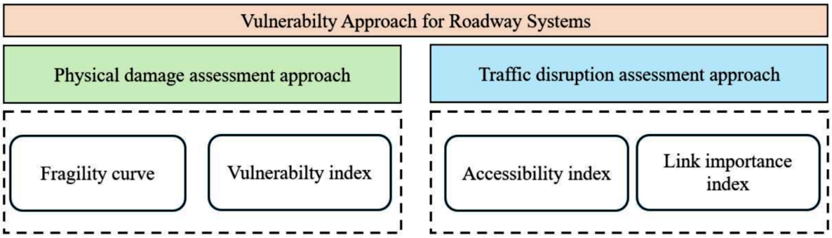

Fig. 2 Vulnerability approach for roadway systems

widely used worldwide and provides an easy-to-understand, direct indicator for engineers, decision-makers, and managers. In earthquake preparedness studies, VI methods involve the determination of an index through an analytical expression that includes the significant parameters affecting the seismic behavior of the system under consideration. These parameters are weighted to reflect their relative contribution to the overall vulnerability, with weights determined by statistical analyses, expert opinions, or multi-criteria decision-making (MCDM) methods (Atanassov 1986).

This study proposes a novel VI-based approach for risk assessment of urban roadway systems. Although the proposed method is similar to that of Adefer and Bensaibi (2017), it aims to contribute to the related literature as summarized below. Considering roadways as a system consisting of various assets, the parameters that may cause vulnerability are divided into two parts: in-system and out-system, with a novel approach. In-system parameters are the parameters that will affect the vulnerability of the roadway in terms of geometry and functionality. Out-system parameters will affect the roadway's vulnerability directly, such as soil conditions, the magnitude of the hazard, etc., or indirectly, such as the collapse of the buildings and road closures.

During the 17 August 1999 Mw 7.4 Izmit earthquake, Avcılar, a suburb of Istanbul, suffered much more damage than neighboring districts located at similar distances and azimuths from the epicenter. Although situated more than 90 km from the fault rupture, strong ground motion caused the deaths of approximately 1000 residents and severe building damage. (Ergin et al. 2004). The Avcılar district has been the research focus for many years, as it was severely damaged after the 1999 Izmit earthquake. While some researchers are investigating the reasons for the severe damage in Avcılar (Dalgıç 2004; Kudo et al. 2002; Özel et al. 2002; Tezcan et al. 2002), most researchers are concerned with risk mitigation and planning for the expected major Istanbul earthquake (Bakir et al. 2007; Eraybar et al. 2010; Önder et al. 2004; Yücel 2018). For this reason, roadways classified as avenue in Avcılar District were selected as the application area of the study.

The proposed method was validated for real cases from the earthquake-affected zone in the February 2023 earthquakes. In this study, parameter weights are calculated separately by the Analytic Hierarchy Process (AHP) and Interval Valued Fermatean Fuzzy Analytic Hierarchy Process (IVFF-AHP), and these two methods are then compared. The AHP method has been used in the literature to determine the parameter weights (Zadeh 1965). However, this study presents a different perspective by using IVFF-AHP, which has not been used before to calculate the parameter weights. Specifically, IVFF-AHP is used to better understand the fuzziness in decision-making and reduce the personalization of decision-maker decisions. A further novelty is that this is the first study in which the IVFF AHP method has been used to assess the vulnerability of urban roads. At the same time, the comparison of weight calculations with the IVFF-AHP and AHP methods has been made in the literature for the first time. This study aims to determine the risk indices of roads in the transportation network, considering the characteristics of the region's infrastructure and buildings and various critical factors. This enables local authorities and engineers to develop alternative contingency plans to minimize human and economic losses during and after earthquakes. The rest of the study is organized as follows: The next section presents the theoretical background and the proposed research methodology. Sections 3 and 4 present a case study with the results. Section 5 gives a validation with real-life data. Section 6 includes the discussion. Finally, Sect. 7 summarizes the conclusions and further research.

2 The steps in the proposed methodology

The flowchart of the proposed methodology is shown in Fig. 3. The first stage is the identification of the VI parameters that can cause roadway damage in a seismic event. Parameters and factors considered in this evaluation are obtained after a detailed literature review. The weights of the selected factors are then calculated using the MCDM, AHP, and IVFF-AHP. In the next stage, VI scores are obtained using the calculated weights detailed in Sect. 2.4.

For the application, the roadway system is first divided into sections by the nodes and edges. The actual data for the factors are aggregated to calculate the VI score for the pathways in each node, and VI score values are calculated for the roadways. The VI scores are acquired to assist in categorizing the roadways into three risk-based groups. Each node is classified, and the roadways with the highest risk are identified.

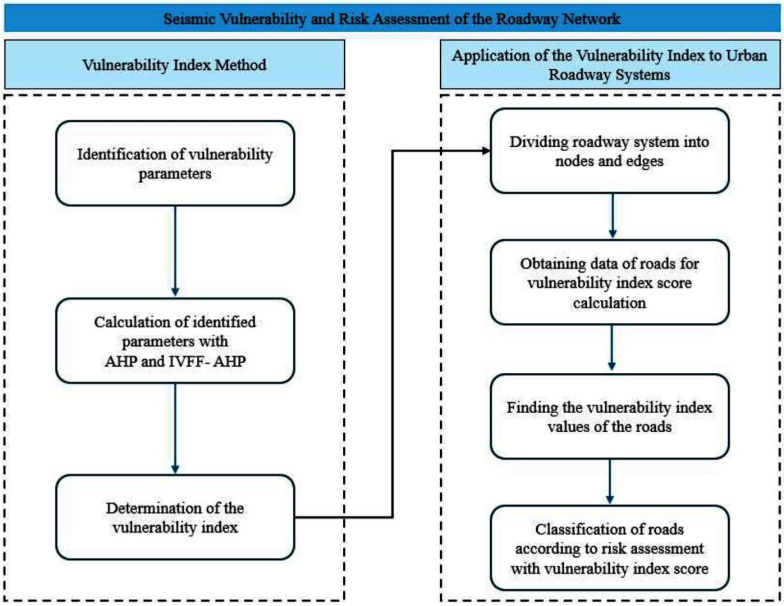

Fig. 3 The proposed methodology

2.1 Identification of vulnerability parameters

The vulnerability of roads depends on the geometric and structural characteristics of the site, as well as its geotechnical and seismic properties. In addition, past earthquakes have shown that building collapses in urban roadway systems significantly impact the vulnerability of roadways (El-Maissi et al. 2023; Goretti and Sarli 2006; Islam et al. 2020). In the literature, VI-based studies have been evaluated based on different parameters. Adefer and Bensaibi (2017) categorized these parameters into two categories: structural and hazardous. Anelli et al. (2020) made two classes, indirect and direct. While direct effects are structural damage and ground collapse, indirect effects are building collapses; rock falls and landslides. Francini et al. (2020) developed a VI for urban roads using four different parameters: (i) the length of the road, (ii) the width of the road, (iii) the redundancy level of the road, and (iv) critical elements (bridges, intersections, underpasses, tunnels, and other elements that could affect the vulnerability of the system).

Based on the literature, this study divides the vulnerability parameters into two categories: in-system and out-system, as shown in Fig. 4. In-system parameters include geometrical and functional characteristics of roads. The out-system parameters are the parameters that directly and indirectly damage the roads.

Table 1 categorizes the selected parameters into factors. The literature was utilized to select the factors, and novel factors were also within the scope of this study.

- Two different in-system parameters were selected. The Number of lanes was considered critical; the narrower the road, the greater the risk of total road closure. Pavement conditions were chosen as the other system parameter, considering that the initial conditions

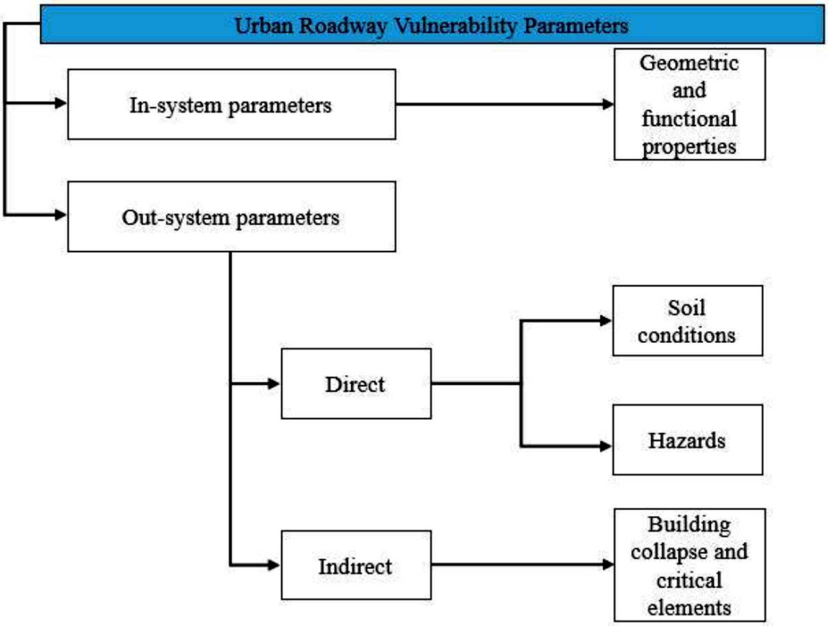

Fig. 4 Urban roadway vulnerability parameters

Table 1 Selected parameters and factors for VI

Parameters	Item	Factor	References
In-system parameters	Geometric and functional properties	Number of lanes	Adefer et al. (2017)
		Pavement conditions (PC)	Adefer et al. (2017)
Out-system parameters (Direct)	Soil condition	Ground type (GT)	Adefer et al. (2017)
	Hazards	Seismic Intensity: PGV	Proposed in this study
		Liquefaction potential Index (LPI)	Adefer et al. (2017)
Out-system parameters (Indirect)	Building collapse	Buildings: year of construction (YC)	Proposed in this study
		Number of storeys in the building (SB)	Proposed in this study
	Critical elements	Intersections, bridges, underpasses, retaining structures, etc.	Francini et al. (2020)

of the pavement impact the level of damage that can occur during an earthquake.

- Direct out-system parameters were chosen as soil conditions and hazards. Soil conditions dictate the level of damage to the pavement and the neighboring structures. Better soil conditions should be correlated with lower damage levels. Regarding hazards, peak ground velocity and Liquefaction Potential Index were included as affecting parameters. PGV values were chosen to characterize seismic demand because reliable data were presented by Maruyama et al. (2010), who generated fragility curves of highway embankments for earthquake risk in Japan. Highway damage datasets were compiled for the 2003 North-Miyagi, 2003 Tokachi-oki, 2004 Niigata Chuetsu, and 2007 Niigata Chuetsu-oki earthquakes, and peak ground velocity (PGV) spatial distributions were estimated for these four earthquakes to assess the relationship between highway embankment damage rate and PGV. Subsequently, a statistical analysis was carried out, and the fragility curves of motorway slopes were drawn. According to the fragility curves, it was stated that when the peak ground velocity exceeds about 35.0 cm/s, major damages occur, disrupting normal highway traffic. Additionally, liquefaction has been observed to be a critical parameter which has damaged the roads in the past earthquakes (Cubrinovski 2013; Papathanassiou et al. 2015, 2016; Verdugo and González 2015; Yasuda et al. 2013). The Liquefaction Potential Index related to liquefaction-related settlements was chosen for liquefaction hazard.
- As indirect out-system parameters, building collapse and the presence of critical elements were selected. The collapse of buildings was assessed based on the year of construction and the number of storeys. An increased number of storeys were considered to bring a higher risk since, in case of collapse, the road's closure is more likely due to more demolished material. Critical elements were also considered since this added extra risk for the road closure in case they collapsed. Other details are presented in Sect. 3.1 of this paper.

2.2 Interval Valued Fermatean Fuzzy Analytic Hierarchy Process (IVFF-AHP)

Fuzzy logic is a valuable approach for process control when information is complicated, nonlinear, and challenging to predict. Fuzzy logic can offer a qualitative evaluation and subjective judgment in complex decision-making situations. Different fuzzy sets can be utilized to generate language phrases to deal with fuzziness and unpredictability in data (Wang et al. 2015). The membership function defines a basic fuzzy set's membership degree μ, and the set's non-membership degree may be calculated using 1- μ. However, in the same circumstances, relying on the membership function might not capture the fuzziness well enough. Different fuzzy backgrounds must be learned for the mathematical framework used for the interval-valued Fermatean fuzzy analytic hierarchy process. Atanassov established the IFS theory, a generalized version of the fuzzy set theory (Atanassov 1986). In addition to the membership function, the non-membership function *v* defines an element in an IFS. Both functions have degrees that range from [0,1]. Atanassov added a third function named hesitancy (π) to make the total of the membership and non-membership degrees equal to 1 (Ayyildiz 2023). All definitions of IFS are given in detail in Atanassov (1986) and Ayyildiz (2023). Pythagorean Fuzzy Sets **(**PFS) created from IF sets, are defined by Yager (Yager 2013). The sum of the membership and non-membership degrees in PFS can be more than 1, but their square sums cannot exceed 1 (Karasan et al. 2018). All definitions of PFS are given in detail in Ayyildiz (2023). The idea of Fermatean Fuzzy Sets (FFS) is described by Senapati and Yager (Senapati and Yager 2019, 2020) as an expansion of IFS and PFS. This set can be considered a novel method of expressing unreliable, murky, and uncertain information in a fuzzy context. Alkan and Kahraman (2022) describe the FFS numbers and mathematical operations.

The mathematical operations of interval-valued Fermatean Fuzzy Sets (IVFFS) have been briefly presented as follows (Jeevaraj 2021):

Definition 1 Furthermore, for each x϶ X, $\mu_{\underset{F}{\sim}}(x)$ and $v_{\underset{F}{\sim}}(x)$ are closed intervals, and their lower and upper limits are represented by $\mu_{\underset{F}{\sim}}^{L}(x)$, $\mu_{\underset{F}{\sim}}^{U}(x)$, $v_{\underset{F}{\sim}}^{L}(x)$, $v_{\underset{F}{\sim}}^{U}(x)$, respectively. As a result, can also be represented as follows:

$$\mu_{\underset{F}{\sim}}(x) = \left[\mu_{\underset{F}{\sim}}^{L}(x), \mu_{\underset{F}{\sim}}^{U}(x)\right] \subseteq [0,1] \tag{1}$$

$$v_{\underset{F}{\sim}}(x) = \left[v_{\underset{F}{\sim}}^{L}(x), v_{\underset{F}{\sim}}^{U}(x)\right] \subseteq [0,1] \tag{2}$$

$$0 \leq \left(\mu_{\underset{F}{\sim}}^{U}(x)\right)^{3} + \left(v_{\underset{F}{\sim}}^{U}(x)\right)^{3} \leq 1 \tag{3}$$

In IVFFS, the hesitancy degree is defined as $\pi_{\underset{F}{\sim}}(x) = \left[\pi_{\underset{F}{\sim}}^{L}(x), \pi_{\underset{F}{\sim}}^{U}(x)\right]$ for every x ϵ X:

$$\pi_{\underset{F}{\sim}}^{L}(x) = \sqrt[3]{1 - \left(\mu_{\underset{F}{\sim}}^{U}(x)\right)^{3} - \left(v_{\underset{F}{\sim}}^{U}(x)\right)^{3}} \tag{4}$$

$$\pi_{\underset{F}{\sim}}^{U}(x)=\sqrt[3]{1-\left(\mu_{\underset{F}{\sim}}^{L}(x)\right)^{3}-\left(v_{\underset{F}{\sim}}^{L}(x)\right)^{3}} \tag{5}$$

One of the most popular MCDM approaches in the literature, Saaty created AHP (Saaty 2008). The method uses a particular format to weigh factors and make decisions in challenging MCDM problems. Traditional AHP is expanded to fuzzy AHP to express human judgment and preference ambiguity. Numerous MCDM problems are studied in the literature. Fuzzy AHP is used in a variety of ways, including intuitionistic fuzzy AHP (Sadiq and Tesfamariam 2009), interval-valued intuitionistic fuzzy AHP (Wu et al. 2013), hesitant fuzzy AHP (Öztaysi et al. 2015), neutrophisophic AHP (Abdel-Basset, Mohamed, et al. 2017), and interval-valued neutrophisophic AHP (Bolturk and Kahraman 2018). Alkan and Kahraman develop IVFF-AHP by combining the IVFF set and AHP to determine the best digital transformation strategy (Alkan and Kahraman 2022).

The followings are the steps of the IVFF-AHP approach suggested by Alkan and Kahraman (Alkan and Kahraman 2022):

Step 1 The criteria and alternatives are determined before constructing the hierarchical structure.

An objective, decision criteria and alternatives are decided for the given situation. The set $A_i = A_1, A_2, \ldots\ldots., A_n$, which has $I = 1,2, \ldots., n$ alternatives, is assessed by *m* decision criteria from the set $C_j = \{C_1, C_2, \ldots\ldots., C_m\}$ which has $j = 1,2, \ldots.m$. Let $w_j = w_1, w_2, \ldots., w_m$ be the vector set used to define the criterion weights, where $w_j > 0$ and $\sum_{j=1}^{n} w_j = 1$. Table 2 lists linguistic terms and their associated IVFFNs.

Step 2 The pairwise comparison matrix Z = is created using the expert views is Table 2.

$$z_{ij} = \langle \left[\mu_{ij}^{L}, \mu_{ij}^{U}\right], \left[v_{ij}^{L}, v_{ij}^{U}\right] \rangle \tag{6}$$

Step 3 Table 2 determines the consistency in the pairwise comparison matrix created according to expert judgments. After matching the numbers obtained from defuzzification with the IVFFNs in Table 2, Saaty's classical consistency steps are followed.

Step 4 Expert opinions are gathered.

Table 2 Linguistic terms and IVFFN equivalents (Alkan and Kahraman 2022)

Linguistic terms	IVFFN equivalents			
	μ_L	μ_U	v_L	v_U
Certainly High Importance (CHI)	0.95	1	0	0
Very High Importance (VHI)	0.8	0.9	0.1	0.2
High Importance (HI)	0.7	0.8	0.2	0.3
Slightly More Importance (SMI)	0.6	0.65	0.35	0.4
Equally Importance (EI)	0.5	0.5	0.5	0.5
Slightly Less Importance (SLI)	0.35	0.4	0.6	0.65
Low Importance (LI)	0.2	0.3	0.7	0.8
Very Low Importance (VLI)	0.1	0.2	0.8	0.9
Certainly Low Importance (CLI)	0	0	0.95	1

The pairwise comparison matrices generated for each expert are combined using the interval-valued Fermatean fuzzy weighted geometric (IVFFWG) aggregation operator. Let Ek = E_1, E_2,...,E_k, with $k = 1{,}2, \ldots .K$, represents the set of experts with influence weights w_k ; $\sum_{k=1}^{K} w_k = 1$.

$$\mathrm{IVFFWG}\left(z_1, z_2, \ldots, z_k\right) = \left(\left[\prod_{k=1}^{K} \left(\mu_k^L\right)^{w_k}, \prod_{k=1}^{K} \left(\mu_k^U\right)^{w_k}\right], x\left[\sqrt[3]{\left(1 - \prod_{k=1}^{K} \left(1 - \left(v_k^L\right)^3\right)^{w_k}\right), \sqrt[3]{1 - \prod_{k=1}^{K} \left(1 - \left(v_k^U\right)^3\right)^{w_k}\right)}}\right]\right) \tag{7}$$

Step 5 The differences matrix $D = \left(Z_{ij}\right)_{mxm}$ is determined between the lower and upper points of the membership and non-membership functions using Eqs. [8] and [9].

$$d_{ij}^L = \left(\mu_{ij}^L\right)^3 - \left(v_{ij}^U\right)^3 \tag{8}$$

$$d_{ij}^U = \left(\mu_{ij}^U\right)^3 - \left(v_{ij}^L\right)^3 \tag{9}$$

Step 6 The interval multiplicative matrix $S = \left(S_{ij}\right)_{mxm}$ is calculated using Eqs. [10] and [11].

$$s_{ij}^L = \sqrt[3]{1000^{d_{ij}^L}} \tag{10}$$

$$s_{ij}^U = \sqrt[3]{1000^{d_{ij}^U}} \tag{11}$$

Step 7 Applying Eq. [12], calculate the indeterminacy value $T = \left(t_{ij}\right)_{mxm}$ of z_{ij}:

$$t_{ij} = 1 - \left(\mu_{ijU}^3 - \mu_{ijL}^3\right) - \left(v_{ijU}^3 - v_{ijL}^3\right) \tag{12}$$

Step 8 Applying Equation [30], multiply the indeterminacy degrees by the matrix $S = \left(s_{ij}\right)_{mxm}$ to create the matrix of unnormalized weights $R = \left(r_{ij}\right)_{mxm}$:

$$r_{ij} = \left(\frac{s_{ij}^L + s_{ij}^U}{2}\right) t_{ij} \tag{13}$$

Step 9 Normalized priority weights (w_i) values are calculated using Equation [14].

$$w_i = \frac{\sum_{j=1}^{m} r_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{m} r_{ij}} \tag{14}$$

Step 10 The alternatives are ranked based on the priority weight values calculated in the previous step.

2.3 Calculation of factors weights

The factors are developed using expert interviews and a literature review. The expert team for this study was used to (i) determine the main factors and (ii) evaluate the factors to determine their weights. In this context, three accomplished professionals have been invited to share their perspectives in the expert group. The experts were chosen based on (i) education in the related field, (ii) familiarity with VI and MDCM, (iii) experience in related fields (5 years at a minimum), and (iv) prior involvement in earthquake research. Expert-1 is a professor with 18 years of academic experience and numerous publications in the field of VI and earthquake-related studies. Expert-2 is a Civil Engineer Ph.D. student with six years of work experience in the related field. Expert-3 is an academician with a Ph.D. in Civil Engineering and ten years of experience in the field. For traditional AHP weight calculation, the steps suggested by Saaty (2008) are followed.

This section applies traditional AHP and IVFF-AHP steps to determine the weights of VI. The following calculation procedure is applied to calculate the weight factors for the IVFF-AHP criteria. Three experts are consulted to give their opinion on the importance of the criteria. After converting the pairwise comparison matrices into IVFFNs with the corresponding scale, the expert assessments are combined with the IVFFWG operator using Eq. [7]. Equations [8] and [9] calculate the difference matrix $D = (d_{ij})_{mxm}$ between the lower and upper values of the membership and non-membership degrees. Then the interval product matrix $S = (s_{ij})_{mxm}$ is found based on Eqs. [10] and [11]. Unnormalized weight matrix is found by using the indeterminacy value calculated using Eq. [12] and the interval product matrix. In the last step, the priority weight value of each criterion is obtained by using Eq. [14]. The criteria weights are presented in Table 3.

The table shows that the seismic intensity has the highest weight, with 0.24. It is followed by Buildings: year of construction, Storey of Building, and ground type with 0.18, 0.17, and 0.12, respectively, for IVFF-AHP. Width of lanes, Liquefaction Potential, and Liquefaction Potential are equally effective with a weight of 0.09. The criterion with the least weight in the VI calculation is Pavement conditions with 0.02. For the traditional AHP method, Ground Type and Buildings: year of construction are in second place with an equal weight of 0.14. Critical Elements, Storey of Building (SB), Number of lanes, Liquefaction Potential, and Pavement conditions come next, similar to IVFF-AHP. In both methods, the factor with the highest weight is the same, but the expert group also examines the change in other factor weights. Notably, the weight changes in the factors important for the study differed in both methods. Therefore, the expert group analyzed the importance of the factors according to the order of importance and the values of the weights. As confirmed by the sensitivity

Table 3 Final weights of criteria with AHP and IVFF-AHP

Main criteria	IVFF-AHP	AHP
Number of lanes	0.09	0.10
Pavement conditions	0.02	0.06
Ground type	0.12	0.14
Seismic intensity	0.24	0.24
Liquefaction Potential	0.09	0.08
Buildings: year of construction	0.18	0.14
Storey of Building	0.17	0.12
Critical Elements	0.09	0.13

analysis in Sect. 4.1, the weights found with the IVFF-AHP method were more precise than the AHP method and gave more accurate results.

3 Application of the model to a real study area

The framework proposed in this study has also been applied to Avcılar district. Avcılar is located west of Istanbul, on the Marmara Sea coast, 27 km from the center of Istanbul. Küçükçekmece Lake and Küçükçekmece district to the east, Yakuplu and Esenyurt, Bahçeşehir and Küçükçekmece in the north; in the south is surrounded by the Marmara Sea. The district is approximately 42.59 km^2. TEM highway and E-5 (D-100) highway pass through the district borders and divide the district into three parts. According to TÜİK 2019 data, the district's population is 448,882 (İBB, 2020). Avcılar district consists of ten neighborhoods: Tahtakale, Yeşilkent, Firüzköy, Mustafa Kemal Paşa, Universite, Cihangir, Merkez, Ambarlı, Denizköşkler and Gümüşpala. These neighborhoods consist of many streets and avenues.

Within the scope of this study, vulnerability assessment was carried out on the roadways considered avenues in Avcılar. The selected roadways were divided into nodes and edges according to two factors. These are;

- One node point was added at the road junction points.
- Based on the added node points, a node point was added again, with a maximum distance between two node points of 500 m.

Figure 5a shows the location of Avcılar District in Istanbul, Fig. 5b shows the selected avenues, and Fig. 5c shows the general views of the selected avenues. Table 4 presents detailed names and node numbers of the avenues.

3.1 Determination of the VI

Table 5 shows the factors selected in Sect. 2.1 and the weights determined in Sect. 2.3 according to the IVFF-AHP method. The scores were established for each category as 3 for the highest risk and 0 for the lowest risk. In the next step, based on the results of the previous stages, the analytical expression of the VI is developed as follows:

$$VI = \sum_{i=1}^{n} W_i . F_i \tag{15}$$

where is;

VI = Vulnerability index for roadway
W_i = Weighting coefficient of factor
F_i = Score of category
n = Number of factors

The parameters were chosen based on the following arguments:

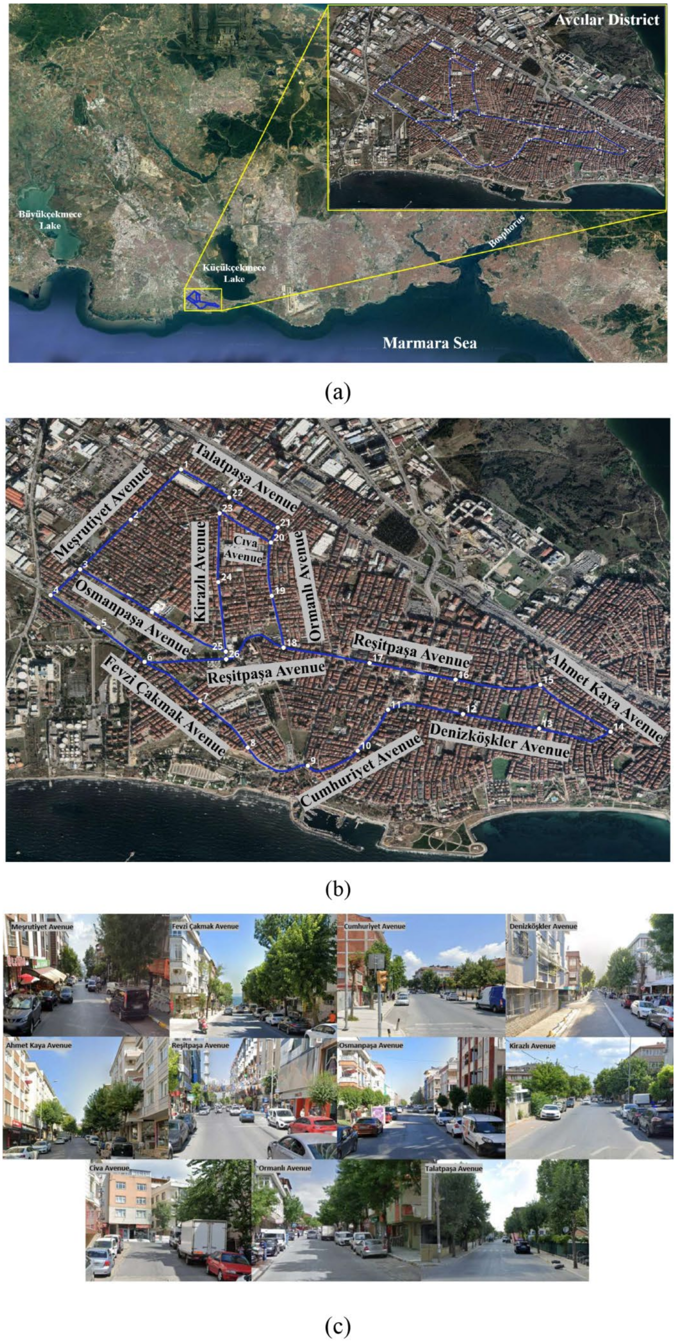

Fig. 5 **(a)** General view of the study area in Istanbul **(b)** Detailed view of the study area **(c)** Typical Avenues in Avcilar

Table 4 Selected avenue name and node number

No	Avenue name	Node number
1	Meşrutiyet	1-2-3-4
2	Fevzi Çakmak	4-5-6-7-8-9
3	Cumhuriyet	9-10-11
4	Denizköşkler	11-12-13-14
5	Ahmet Kaya	14–15
6	Reşitpaşa	15-16-17-18-26-6
7	Osmanpaşa	25-27-3
8	Kirazlı	22-24-25-26
9	Cıva	20–22
10	Ormanlı	18-19-20-21
11	Talatpaşa	21-22-1

Table 5 Proposed factors, weights, categories, and scores

Factor	Weights	Category	Score
Width of lanes	0.09	≤2 lanes	2
		>2 lanes	1
Pavement conditions (PC)	0.02	Low	3
		Medium	2
		High	1
Ground type (GT)	0.12	ZE-ZF	3
		ZC-ZD	2
		ZA-ZB	1
Seismic Intensity: Peak Ground Velocity (PGV) (cm/s)	0.24	>40	3
		35–40	2
		<35	1
Liquefaction Potential Index (LPI)	0.09	15<LPI	3
		5<LPI≤15	2
		0<LPI≤5	1
		LPI=0	0
Buildings: year of construction (YC)	0.18	<1980	3
		1980–2000	2
		>2000	1
Storey of Building (SB)	0.17	>5 storey	3
		3–5 storey	2
		<3 storey	1
Critical Elements	0.09	Yes	2
		No	1

- Roads are evaluated based on whether the number of lanes is more or less than two.
- Pavement condition includes evaluation of pavement rutting, patching, and surface cracks and is categorized as low, medium, and high.
- Ground type is categorized according to the Türkiye Building Earthquake Regulation, TBDY (2018), the Turkish seismic code. In this code, different soil groups (ZA, ZB, ZC, ZD, ZE, and ZF) are classified according to subsurface conditions. ZA soils are rocky subsoil conditions, whereas ZE and ZF represent the most problematic soil conditions during an earthquake. The others are in between.

- The PGV value is determined according to the Istanbul Probable Earthquake Damage Estimates Booklet (IBB 2020).
- Liquefaction hazard is evaluated according to the Liquefaction Potential Index proposed by Iwasaki et al. (1982).
- The risk of building collapse is taken as a function of the year of construction. After the 1999 Adapazari Earthquake in Turkey, the quality of building construction methods, materials, and manufacturing control increased due to newly published Earthquake Codes and other control mechanisms (TBDY 2018). For this reason, buildings are evaluated based on pre-1980, between 1980 and 2000, and post-2000.
- The storey of buildings is categorized according to the Istanbul Probable Earthquake Damage Estimates Booklet (IBB 2020). The higher the buildings, the more debris will be affecting the road.
- Intersections, bridges, underpasses, and retaining structures are evaluated as critical elements.

Table 6 details the data sources and gathering methods for the categorized factors. Based on the data, scores were assigned for each node interval (Table 5).

4 Results of the case study

The proposed method was applied to the Avcılar district in İstanbul, Türkiye. The results are shown in Fig. 6. According to Fig. 6, the highest VI value is obtained for the roadway between nodes 9 and 10 of Cumhuriyet Avenue. In contrast, the lowest VI value is obtained for the roadway between nodes 25 and 26 of Kirazlı Avenue. While the VI value between

Table 6 Data source and gathering method

Factor	Data source	Data gathering method
Number of lanes	Observation	In-situ measurement and Satellite Image
Pavement conditions	Observation	In-situ measurement
Ground type	Istanbul European Side South Microzonation Study (İBB 2007)	Maps
Seismic intensity	Istanbul Probable Earthquake Damage Estimates Booklet (İBB 2020)	Maps
Liquefaction Potential Index	Istanbul European Side South Microzonation Study (İBB 2007)	Maps
Buildings: year of construction	Istanbul Probable Earthquake Damage Estimates Booklet (İBB 2020)	Maps and GIS
Storey of Building	Istanbul Probable Earthquake Damage Estimates Booklet (İBB 2020)	Maps and GIS
Critical Elements	Observation	In-situ measurement and Satellite Image

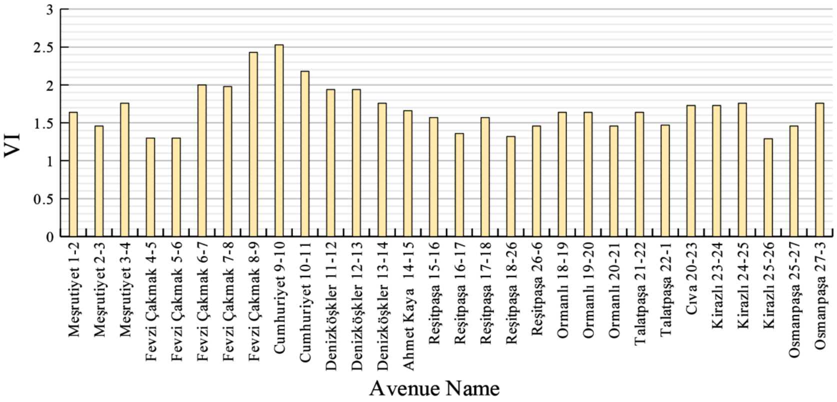

Fig. 6 VI values for the study area

Table 7 Developed VI rating

VI rating code	Limit value of VI	Description	Legend
VR1	0.80–1.44	Low Risk	🟩
VR2	1.44–2.09	Moderate Risk	🟧
VR3	2.09–2.73	High Risk	🟥

nodes 9–10 on Cumhuriyet Avenue is 2.53, the VI value between nodes 25–26 on Kirazlı Avenue is 1.26. The VI values between Cumhuriyet 9–10 nodes are followed by Fevzi Çakmak Avenue 8–9 nodes and Cumhuriyet Avenue 10–11 nodes with VI values of 2.43 and 2.18, respectively. The arithmetic means of the VI values calculated at 30 edges in the study area is 1.69. The VI between 13 nodes is above average.

The VI values obtained are divided into three ranges to interpret better the VI values calculated between the selected nodes, and a VI Rating is developed. The details of the developed VI rating are presented in Table 7.

The VI values are visualized in Fig. 7. The results can be summarized as below;

- Fevzi Çakmak Avenue between nodes 8–9, Cumhuriyet Avenue between nodes 9–10 and 10–11 are considered high risk (VR3),
- Fevzi Çakmak Avenue between nodes 4–5 and 5–6, Reşitpaşa Avenue between nodes 16–17 and 18–26, Kirazlı Avenue between nodes 25–26 is considered low risk (VR1).
- The inter-point intervals on the remaining avenues were calculated as medium risk (VR2).
- Fevzi Çakmak Avenue between nodes 8–9, Cumhuriyet Avenue between nodes 9–10 and 10–11 is located at the southern end of the study area. The high-risk assessment of this region is attributed to its liquefaction potential and high PGV values.
- Fevzi Çakmak Avenue between nodes 4–5 and 5–6, Reşitpaşa Avenue between nodes 16–17 and 18–26, and Kirazlı Avenue between nodes 25–26 is considered to have low risk (VR1) because the density of the building stock is relatively lower at the location of the roadway compared to other nodes.

Fig. 7 Implementation of categorized VI values in the study area

4.1 Sensitivity

A sensitivity analysis based on altering the criteria weights is carried out to show the stability of the suggested method. For this analysis, eight weight sets are created by changing the weights found with the IVFF-AHP method. Sensitivity aims to see the impact of changing the criteria weights. It can be easily observed from Fig. 8 that the best (rank 1) and worst (rank 30) examples remain the same for all ranking models. Therefore, the ranking results of the proposed methodology are very stable even when the criteria weights are changed.

5 Validation of VI

Türkiye has experienced an enormous loss of life and property due to two major earthquakes centered in Kahramanmaraş, which occurred at intervals of nine hours. Earthquakes in the East Anatolian Fault Zone (EAFZ), one of Türkiye's main tectonic structures, caused hefty damage in 11 cities. The first earthquake occurred in Pazarcık, Kahramanmaraş ($Mw = 7.7$) on 6 February 2023 at 04:17 and lasted approximately 75 s. The second earthquake occurred on the same day at 13:24 in Elbistan, Kahramanmaraş ($Mw = 7.6$), and lasted approximately 25 s (Işık et al. 2024). These 2023 Turkiye earthquakes affected more than 15 million people in the cities of Kahramanmaraş, Adıyaman, Antakya/Hatay, Osmaniye, Malatya, Gaziantep, Şanlıurfa, Diyarbakır, Adana, Elazığ, and Kilis and caused intense shaking and damage. The approximate number of casualties exceeded 45,000, and more than 120,000 buildings collapsed or were heavily damaged (AFAD 2023).

2023 Kahramanmaraş Earthquakes also caused damage to roadway systems. In this study, roadway damages in Gölbaşı District of Adıyaman Province were selected to validate the proposed method. Gölbaşı District is located on the Gaziantep-Malatya highway

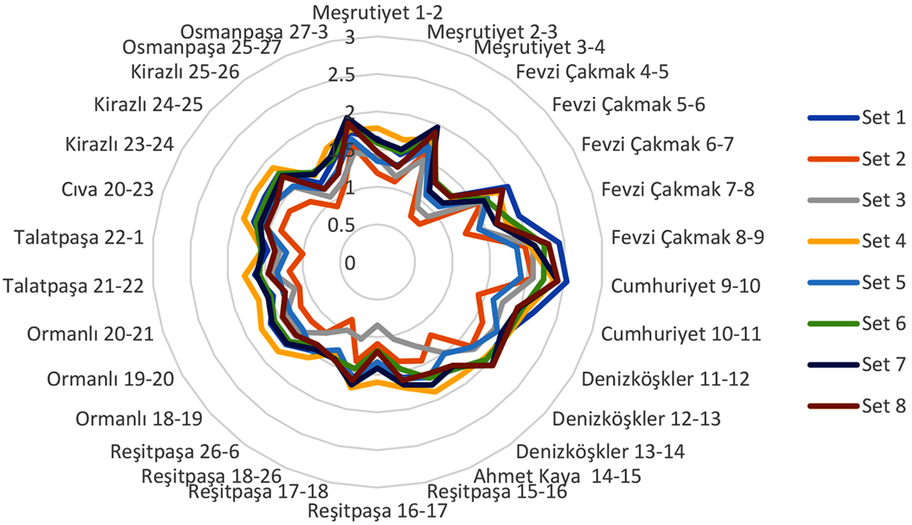

Fig. 8 Alternative ranking according to different criteria weights

Fig. 9 Gölbaşı Disrict location

and Adana-Malatya railway route connecting the Eastern Mediterranean and Southeastern Anatolia regions to Eastern Anatolia. Gölbaşı is 62 km from Adıyaman, 105 km from Malatya, 100 km from Kahramanmaraş and 122 km from Gaziantep (Tonyalı et al. 2024) (Fig. 9). Tectonics The district, which is adjacent to Gölbaşı Lake, is located on the Gölbaşı-Türkoglu fault segment, which is part of the Eastern Anatolian Fault Zone (DAFZ) (Şaroğlu et al. 1987).

The roadways of 5th and 75th Streets in the Gölbaşı district were severely damaged and could not be used in the February 6 earthquakes (Figs. 10 and 11). While 5th Street was damaged by liquefaction, 75th Street was damaged by the loss of bearing capacity and the roadway being blocked by the rotating building.

Fig. 10 Site map and earthquake damage on 5th Street

Fig. 11 Site map and earthquake damage on 75th Street

Table 8 shows the calculated VI values for 5th Street and 75th Streets. While the VI value of 5th Street is calculated as 2.27, the VI value of 75th Street is 2.26. According to the VI rating presented in Table 6, both streets are classified as high-risk (VR3). The risk class in the proposed method is consistent with the incurred damage.

6 Discussion

The methodological framework proposed in this study utilizes the IVFF-AHP method to assess the vulnerability of urban road infrastructure comprehensively. This approach is notable for its ability to integrate both quantitative and qualitative factors and provides a nuanced analysis of road vulnerability. AHP is the most commonly used MCDM method in the literature, especially in earthquake-related studies. IVFF-AHP, in this study, provides a

Table 8 Calculation of Vulnerability Index (VI) to 5th street and 75th street in Gölbaşı

Factor	Weights	Category	5th street Score	75th street Score
Width of lanes	0.09	≤2 lanes	2	2
		>2 lanes		
Pavement conditions (PC)	0.02	Low		
		Medium	2	2
		High		
Ground type (GT)	0.12	ZE-ZF		
		ZC-ZD	3	3
		ZA-ZB		
Seismic Intensity: Peak Ground Velocity (PGV) (cm/s)	0.24	>40		
		35–40	3	3
		<35		
Liquefaction Potential Index (LPI)	0.09	15<LPI		
		5<LPI≤15	3	3
		0<LPI≤5		
		LPI=0		
Buildings: year of construction (YC)	0.18	<1980		
		1980–2000	2	1
		>2000		
Storey of Building (SB)	0.17	>5 storey		
		3–5 storey	2	3
		<3 storey		
Critical Elements	0.09	Yes	0	0
		No		
VI			2.27	2.26

powerful tool to address the complexity and uncertainty inherent in earthquake scenarios. The linguistic scale used is more detailed than AHP, allowing it to express the fuzziness of decisions better. This provides a structured framework integrating expert judgment and quantitative analysis, improving the ability to make informed, objective, and effective risk assessment, resource allocation, and post-disaster recovery decisions.

The methodology allows for a detailed assessment that considers the interdependencies between damaged buildings, road networks, and disaster response mechanisms by assigning a risk factor to each road section. An important aspect of the study is its application to Istanbul, Turkey, a city with high seismic risk. The real case study effectively demonstrates the methodology's ability to identify and quantify vulnerabilities in the transportation network. Identifying high-risk areas is particularly valuable for urban planners and policymakers as it enables targeted mitigation measures to increase infrastructure resilience. Furthermore, the validation of the methodology in Gölbaşı district of Adıyaman underlines its practical applicability and robustness. This real-world validation confirms the framework's effectiveness in assessing and responding to seismic risks, thus increasing its credibility and potential for broader application.

While the study presents several limitations, it should be acknowledged. The effectiveness of the IVFF-AHP heavily relies on the availability and accuracy of data, which can be challenging to obtain, especially in developing regions. The selection and weighting of criteria in the AHP framework involve subjectivity, potentially affecting the consistency and reliability of the results. Additionally, the complexity of the model may limit its practical application in areas lacking specialized knowledge. Scalability issues arise when applying the framework to large urban areas or multiple cities due to the detailed assessment required for each road section. The dynamic nature of seismic risk necessitates regular updates and recalibrations to maintain accuracy, which can be resource-intensive. Addressing these limitations in future research could enhance the methodology's robustness and applicability, making it a more versatile tool for assessing and improving urban road infrastructure resilience in various seismic-prone regions.

From a methodological point of view, the new approach is an opportunity to utilize multi-criteria analysis alongside fuzzy logic to quantify typically qualitative judgments. At the same time, this approach facilitates a straightforward interpretation of outcomes and allows for comparisons across different factors by utilizing indexes. Moreover, it assesses the interplay among various physical components within the urban landscape, such as buildings and road infrastructures, while accounting for these elements' potential susceptibility to seismic events.

7 Conclusions

This study addresses the assessment of the vulnerability of roads to seismic activity. The approach presented in this paper offers a vulnerability index value for urban roads in case of seismic activity, and it is aimed that these index values help prioritize interventions and guide mitigation measures. It is crucial to interpret the vulnerability index to identify intervention priorities and determine when to take preventative actions to minimize damage used by urban planners, civil engineers, policymakers, and disaster management authorities.

The first stage is an in-depth analysis of the factors that influence roads in an earthquake. The assessment showed that roads' vulnerability depends on various factors, including in-system and out-system parameters. Each component's contribution to vulnerability was assessed through a comprehensive weight analysis using IVFF-AHP and AHP. The proposed VI equation is applied to the roadways characterized as avenues in the Avcılar district of Istanbul, and roadway sections with different levels of risk are identified. Moreover, validation has been performed by applying the method to the Gölbaşı district, which suffered from seismic events in 2023.

The information obtained in this article can contribute to future studies. The obtained VI can be applied to other districts in Istanbul and Türkiye's provinces with high earthquake risk. Regarding methodology, the weights calculated for the VI can be compared with those of different MCDM methods.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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