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Evaluation of Metaverse traffic safety implementations using fuzzy Einstein based logarithmic methodology of additive weights and TOPSIS method

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A R T I C L E I N F O

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A B S T R A C T

As the Metaverse's popularity grows, its effect on everyday problems is beginning to be discussed. The upcoming Metaverse world will influence the transportation system as cross-border lines blur due to rapid globalization. The purpose of this paper is to investigate the capabilities of the Metaverse and its alternatives to traffic safety, as well as to prioritize its advantages. The case study is based on a densely populated metropolis with an extensive education system. The city's decision-makers will have to weigh the pros and cons of the Metaverse's effect on traffic safety. To illustrate the complex forces that drive the decision-making process in traffic safety, we create a case study with four alternatives to Metaverse's integration into the traffic system. Alternatives are evaluated using twelve criteria that reflect the decision problem's rules and regulations, technology, socioeconomic, and traffic aspects. In this study, fuzzy Einstein based logarithmic methodology of additive weights (LMAW) is applied to calculate the weights of the criteria. We present a new framework that combines Einstein norms and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to rank the alternatives. The findings of this study show that public transportation is the most appropriate area for implementing the Metaverse into traffic safety because of its practical opportunities and broad usage area.

1. Introduction

Every year, nearly 1.3 million people die as a result of traffic accidents worldwide, while 20 to 50 million people suffer from non-fatal injuries and disabilities (WHO, 2022). The traffic safety system approach includes human errors as one of the most important risk factors. In the real world, most accidents occur as a result of poor vehicle management. According to research conducted by the Government of Jharkhand, India, the main causes of accidents are excessive speeding, drunken driving, distractions to the driver, red light jumping, and failure to wear safety equipment such as seat belts and helmets (Transport Department of Jharkhand Government, n.d). Furthermore, statistics on fatal crashes in the United States, for example, show how single-vehicle, run-off-road accidents have increased dramatically (National Highway Traffic Safety Administration, 2019). The number of countries may be increased because the global rate of vehicle ownership is increasing,

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resulting in unsafe driving. Under the leadership of China and the United States, there are nearly 1.45 billion cars in the world in 2021 (Hedges and Company, 2022), with the number expected to triple by 2050. According to American Automotive Association, the average car ownership cost in 2021 for vehicles driven 15,000 miles per year was $9666 per year, or $806 per month (Newsroom, 2021). These figures do not even include the number of junked vehicles each year. As a result, accidents, deaths, and enormous costs show that driving in the real world can be less safe.

The Metaverse has acquired popularity since 2021, particularly after Facebook and Microsoft's investments. Overall, it is the incorporation of physical and digital space into a virtual universe. It is based on virtual reality and augmented reality (AR) technologies that enable multimodal interactions with digital elements, virtual environments, and people (Pamucar et al., 2022). Users can access the Metaverse through extended reality (XR) and user interaction techniques (e.g., manipulating virtual objects). Through user interaction and XR, computer vision (CV), artificial intelligence (AI), blockchain, and robotics/Internet of Things (IoT) can collaborate with the user to handle various activities within the Metaverse (Huynh-The et al., 2022). As a result, this three-dimensional world permits individuals to experience lifelike events (Kelly et al., 2021).

Without a doubt, the Metaverse world will have positive effects on numerous fields, including the transportation system, which includes logistics and urban mobility. The ultimate benefits of the Metaverse could be the optimization of transportation processes via navigation, load, and the eradication of cost overruns. Under the dominance of the Metaverse, this relationship does not have a unilateral effect. Smart communities, smart buildings, and smart transportation may eventually adopt unified data standards and merge to form a smart city Metaverse (Global XR Insight, 2022). While it is believed that the traffic problems will be resolved as a result of this collaboration, safety may also be enhanced and accidents may be avoided.

In this way, the predictive features in the Metaverse world will mostly ensure safety by preventing deaths and fatal injuries. The most effective ones might be 3D and 5G wireless technologies, and 3D convolution for intelligent cellular traffic forecasting, in which the deep model can learn the underlying traffic data correlations in both short-term and long-term spatial patterns (Huynh-The et al., 2022). Furthermore, Gao et al. (2022) demonstrate that an AR-based driver-assistance interface optimizes situational awareness for driving and monitoring partially autonomous vehicles by focusing on a user interface based on augmented reality.

Recent trials involving the implementation of AR have aimed to reduce negative road management outcomes. For example, the Mcity Test Facility at the University of Michigan uses augmented reality to test drive cars. To test driving safety, testing and interaction between a real test vehicle and virtual vehicles are created during implementation. WayRay establishes an AR-based navigation system that provides the driver with highly precise route and environment information in real-time, thereby improving road safety (Hang Lee et al., 2021). One of the tests performed in Thailand found that the HDAR System Driving Assistance System can help reduce operational costs, and can help drivers achieve higher efficiency so that drivers can control the vehicle to run safely within their traffic lane while driving on the highway (Thiparpakul et al., 2022).

As a result, the four alternatives proposed in this study will aid in understanding the Metaverse's application in traffic safety. It will first be used as a driving instructor for inexperienced drivers. It will also be used to train and manage public transportation vehicles and drivers. Third, Metaverse's implementation will serve as a safety check for sharing economy implementations in traffic. Finally, implementing safety drivers for traffic crash hotspots in the Metaverse will reduce accidents. These alternatives will be developed using four aspects and twelve criteria.

This study differs from previous research in that it focuses directly on traffic safety implementations on traffic safety. In other words, it proposes and develops some alternatives for a field that has not yet been investigated. Some methods are required for decision-makers to prioritize the alternatives mentioned above. Using decision-making tools not only enhances the quality of services provided to users in real-time, but also reduces operational and maintenance expenses (Huynh-The et al., 2022). However, the multi-criteria decision-making method is used in this study, which is more general and flexible than traditional fuzzy techniques. Most multi-criteria models base some parameters on the decision maker's subjective preferences, depending on the conditions under which the decision maker's perception is modeled (Deveci et al., 2022; Zeng et al., 2022; Cui et al., 2021; Cui et al., 2022; Dahooie et al., 2021; He et al., 2021).

Because the Metaverse is new to users and services, this study fills a gap that has not been actively investigated previously. The study's main goal is to elaborate on the Metaverse's role through the potential applications it includes for traffic safety. In this regard, it is the first study to elaborate on these potential applications more thoroughly and comprehensively. Therefore, the fuzzy hybrid approach is based on the fuzzy TOPSIS and Einstein norms to develop a decision-making approach for determining the most suitable alternatives.

Complex situations in which objective and efficient decision-making are required imply the installation of mechanisms/algorithms for rational understanding of attribute relationships and elimination of the influence of extreme/awkward data. In this study, to overcome the described problem in the TOPSIS model, the application of fuzzy Einstein functions for the aggregation of the values of the initial decision matrix is proposed. Fuzzy Einstein functions make it possible to appreciate the interconnections between criteria and their fusion into a unique criterion value. By applying fuzzy Einstein functions, it is possible to effectively represent mutual relations between criteria in the TOPSIS model and eliminate the influence of linear dependencies on attributes.

Fuzzy Einstein TOPSIS methodology has nonlinear fuzzy Einstein functions that enable complex and uncertain information processing in real applications. The proposed flexible nonlinear function improves the flexibility of the traditional TOPSIS method, and additionally objectifies reasoning when solving real decision-making problems. Also, by introducing additional stabilization parameters into the fuzzy Einstein TOPSIS model, the flexibility of the TOPSIS methodology has been improved. Aggregation functions implemented in the proposed multi-criteria framework enable the aggregation of individual and group information, which increases the generalization of the proposed model and enables its application in both individual and group decision-making.

Fuzzy Einstein logarithmic methodology of additive weights (fuzzy E-LMAW) method belongs to the group of subjective models used for defining weight coefficients of criteria. Most subjective models are based on comparisons in pairs of elements of the home matrix, which can increase the number of comparisons in the case of a larger number of criteria. A larger number of criteria for comparison lead to a decrease in the consistency of information, thereby impairing the quality of the obtained solution. The LMAW method allows decision-makers to perceive the relationship between criteria better since it considers the relationships between adjacent criteria. This eliminates the problem of defining the relationship between distant criteria, which leads to a decrease in the consistency of the results of models such as Analytic Hierarchy Process - AHP (Saaty, 1980), Decision-Making Trial and Evaluation Laboratory - DEMATEL (Gabus and Fontela, 1972), Measuring Attractiveness by a Categorical Based Evaluation Technique - MACBETH (Bana et al., 1994) or Best Worst Method - BWM (Rezaei, 2015) method. By considering adjacent criteria, the quality of the obtained solution increases in cases with a larger number of criteria (more than eight).

On the other hand, it is almost impossible to get consistent results in models such as AHP, DEMATEL, BWM, or MACBETH model. This is due to the small range of scales used for comparison (Asadabadi et al., 2019).

The small range of pre-defined scales for comparison makes it difficult to objectively represent expert preferences since it is reduced to the maximum ratio n:1, where n represents the number of elements in the scale. This limitation leads to inconsistencies in the comparisons, thus distorting the representation of expert preferences (Mukhametzyanov, 2023). In the fuzzy E-LMAW model, this problem is eliminated through the possibility of applying any scale, thus giving freedom to decision-makers to express their preferences and relationships between criteria objectively. To summarize, the fuzzy E-LMAW model enables decision-makers to define the relationships between criteria objectively, contributing to expert preferences' objective representation.

The advantages of the proposed method are as follows: (i) Fuzzy Einstein TOPSIS methodology has nonlinear fuzzy Einstein functions that enable the processing of complex and uncertain information that exists in real applications; (ii) The proposed flexible nonlinear function for aggregating information in the home matrix improves the flexibility of the traditional TOPSIS method, and additionally objectifies reasoning when solving real decision-making problems; (iii) By introducing additional stabilization parameters, the flexibility of the TOPSIS methodology has been improved; (iv) An improvement of the Logarithmic Methodology of Additive Weights based on Einstein (E-LMAW) for determining the weighting coefficients of the criteria is proposed. The proposed E-LMAW methodology eliminates the problem of defining relationships between distant criteria; (v) The proposed E-LMAW methodology enables decision-makers to objectively define relationships between criteria, which contribute to the objective representation of expert preferences.

The remainder of this paper is structured as follows. In Section 2, a background on Metaverse is presented. The problem definition is provided in Section 3. In Section 4, the background including concepts of fuzzy Einstein norms, definitions to be used in the study, and the proposed methods are introduced. The case study, the results of the proposed model, and the sensitivity analysis are given in Section 5. In Section 6, the discussions of ranking are presented. The policy implication is given in Section 7. Finally, the conclusions, limitations, and future works are presented in Section 8.

2. Literature review

The incorporation of traffic safety alternatives into the Metaverse has numerous advantages, including the ease of transportation in the VR medium and the advancement of other transportation technological devices. Recent 3D virtual networks necessitated the incorporation of numerous transportation systems into the Metaverse world. This integration should be considered in light of the rising rates of travel and transportation around the world over the last two decades. Although scholars have conducted some research on the Metaverse and transportation, the issue of traffic safety and how to improve it through the metaverse has not been investigated.

A study on one aspect of what makes the cognitively intelligent vehicle more appealing to both drivers and passengers reveals some of the issues. These characteristics are categorized as self-healing, self-integrating, self-learning, and self-driving (Abduljabbar et al., 2019), and their contributions to aviation, shared mobility, intelligent urban mobility, and autonomous vehicles are discussed in terms of AI in transportation. In this way, AI also assists inexperienced drivers, making traffic safer.

In a study based on the cities of Beijing and Shanghai, the optimization objective and practical and feasible optimization method of a public transit network are provided, and an optimized model of the public transit network with improved network efficiency is constructed (Wang et al., 2021). As a result, many other researchers have used genetic algorithms to analyze the effectiveness of the optimization scheme using bus GPS and IC card data. These studies track the time passengers spend getting on and off the bus to estimate the time and economic cost of the vehicle. As a result, they created a multi-intelligence dynamic optimization system (Zhang and Cui, 2019; Xiofaei et al., 2017). All of these discoveries lay the groundwork for understanding how to train and manage public transportation vehicles and drivers to improve traffic safety.

Nansubuga and Kowalkowski (2021) focused on carsharing and prepare a detailed review of the implementation of the sharing economy. In addition to suggestions, which impose some responsibilities on managers, policy implications are proposed by taking into account the potential of carsharing to address many pressing societal and environmental challenges such as traffic congestion and air pollution. Because the major challenges encountered in the real world do not exist in the virtual world, the sharing economy, such as carsharing or bicycle sharing, has the potential to make traffic safer.

The proposals for traffic safety have had a significant effect on the sustainability of the alternatives. There have been studies that show that data-driven intelligence improves taxi drivers safety records (Huang et al., 2021; Yingda et al., 2022). The study of taxicab service optimization using spatiotemporal implementation for hot-spot analysis with taxi trajectories includes a case study that traces the visibility of hot spots in Seoul. According to the study, combining the two types of hot spots can provide new insights for both the public and commercial sectors to maximize taxi service efficiency and reduce idle fuel usage: First, there are taxis without passengers available to pick up passengers, and second, there areas where people are having difficulty hailing a taxi due to the high demand for taxis (Yun et al., 2016).

Recent traffic safety studies provide more information on the incorporation of augmented reality or other technologies into vehicles. The Gaussian process, background subtraction method, and the Kalman filter are introduced to construct a traffic safety detection system in research that proposes a digital twin frame based on a vehicle VR system (Lv et al., 2022). These technologies play an important role in predicting vehicle driving states to improve the accuracy of traffic safety detection. Furthermore, it has been demonstrated that eye tracking in virtual reality can be used successfully to evaluate interactive cognitive systems involved in navigation and action planning based on a new educational curriculum in a traffic safety training setting (Skjermo et al., 2022). Image segmentation and other visual-dimensional tools can provide precise data. If we consider Image Segmentation, Artificial Intelligence for Object Detection, and Visual Simultaneous Localization and Mapping of the 3-Dimensional Model, it is expected that these technologies will significantly improve performance such as computing speed and accuracy for AR applications in automotive vehicles (Weber et al., 2023).

The research in the literature significantly contributes to traffic safety; however, because the Metaverse is a new technology, there has been no research on the combination of these two and their combined effect. The goal of this study is to close that gap by recommending alternatives and contributing to early implementation. Decision-makers will need to focus on these gathered and reinforced alternatives when considering smart cities and traffic safety.

3. Problem definition

This study aims to address the critical issue of traffic safety, which causes 1.3 million deaths per year. The study explores the potential of Metaverse technologies to improve traffic safety and ease of transportation. The proposed alternatives include improving road infrastructure and safety measures, implementing virtual driver training and education programs, utilizing Metaverse technology to monitor and regulate traffic flow, and introducing self-driving vehicle technology integrated with the Metaverse. The study defines 12 criteria, including a reduction in the number of traffic accidents, the cost-effectiveness of implementing Metaverse technology, user experience and satisfaction, and legal and regulatory compliance, among others. By evaluating these alternatives and criteria, the study aims to demonstrate the positive effects of Metaverse technologies on traffic safety and transportation.

3.1. Definition of alternatives

A_1: Used as a tutor for inexperienced drivers: In this alternative, a system will give directions to inexperienced drivers, assist them in emergency maneuvers, and take control of them in real-time. This assistant will appear as a hologram or as a virtual family member next to the driver. When they are supposed to assist, they will control the vehicle remotely. This alternative demonstrates how the Metaverse implementation will benefit both private and company vehicles. Its assistance via various technologies will make transportation and traffic safer, as well as reduce costs and crashes by remotely controlling cars.

A_2: Used for training, and managing public transportation vehicles and drivers: Bus routes and bus stops form a complex network that shapes urban public transportation. As long as AR/MR improves road safety, they will be useful for training and managing vehicles and drivers of public transportation (Goldbach et al., 2022). In general, these tools eliminate the potential dangers posed by drivers in public spaces. Consequently, this alternative is proposed for unanticipated situations during the operation of public transportation. If a driver suffers a heart attack or loses vehicle control, Metaverse technology will manage the vehicle to ensure passenger safety. Therefore, it will make this alternative well-organized by aiding in the development of an efficient vehicle tracking system for public transportation drivers and by providing them with training. Moreover, when planning a bus route, a tram line, or a subway line, it is imperative to use AI during tests and operations (Pamucar et al., 2022).

Consequently, the use of public transportation in the Metaverse will ensure the optimization of public transportation in the real world, as public transportation is the foundation of urban mobility. Moreover, driver errors will be reduced, as Hang Lee et al. (2021) provide an example of how the Metaverse can be used to prevent virtual entities from appearing in front of the windshield of vehicles.

A_3: Used as a safety check for sharing economy implementations in traffic: The sharing economy has the potential to boost productivity, save money, monetize unused resources, and benefit society and the environment (Shaheen and Cohen, 2021). Micro-mobility, or the shared use of bicycles, scooters, or other low-speed modes of transportation, are novel modes of transportation (Pamucar et al., 2022). The use of the Metaverse can help with identity verification and payment processing via blockchain technology and avatars. The Metaverse has the potential to enable sharing economy implementations in traffic safety. Passengers can relax in the comfort of having a professional driver control the car while enjoying complete privacy when a qualified driver operates a shared vehicle remotely from a compact driving station.

A_4: Used as a hotspot safety driver in the metaverse: Hotspots are areas with a high volume of traffic accidents. Hotspots that are related to time, space, and the distribution of points of interest help determine the location of the accidents (Dawar and Deulkar, 2021). Although sending SMS alerts to drivers as they approach hotspots may be one way to improve safety. However, one study found that the time required to respond to tactile stimuli was significantly shorter, followed by auditory stimuli, and then visual stimuli (Ng and Chan, 2012).

The Metaverse field will inevitably be used in countries and cities, and traffic safety becomes a critical issue that must be addressed. Decision-makers must prioritize the potential alternatives and benefits of the Metaverse on traffic safety in this manner. All of these alternatives may be proposed in some ways because the infrastructure of this implementation must be supported to take full advantage. In other words, the Metaverse has the potential to significantly improve traffic safety.

The four aspects are the rules and regulations aspect, the technology aspect, the social aspect, and the traffic aspect, all of which are indicators of the benefits of proposed alternatives. Some criteria, on the other hand, are required to ensure these aspects.

3.2. Definition of criteria

In this study, twelve criteria under four aspects are determined and defined as follows:

(1) Rules and Regulations Aspect

C_1: Privacy concerns (cost): Due to many activities like sharing, cooperating, and increasing mutual trust and understanding in the Metaverse, most users may be unwilling to be included in that process with their user information because the content is highly private and sensitive (Zhao et al., 2022). Some problems may occur regarding privacy issues in the four proposed alternatives. Although the driver may feel safe when the hologram of a family member appears in the first alternative, it may create a problem during the implementation of car-sharing. When it comes to the fourth alternative, a state officer appears via hologram close to the hot spots. The drivers may wonder about their privacy, but because it is merely a hologram, it may be disregarded.

C_2: Challenges in interoperability across platforms and devices and jurisdictions (cost): When it comes to traffic safety, jurisdiction varies from country to country and city to city depending on transportation systems. As a result, when it comes to applications, the standards and regulations may differ. Because the level of development in the application varies, such concerns may cause additional issues in terms of jurisdiction when moving from one province to another. Countries such as the United States may create a space in which this problem is more visible because traffic rules and implementations vary from county to county (Carvalho and Granville, 2022).

C_3: Concerns and challenges relating to cybersecurity (cost): All four alternatives mentioned above are vulnerable to cybersecurity risks, which means the system could be hacked by anyone and many problems could arise as a result of the attack. Nonetheless, this dangerous situation may be brought under control during the fourth option, as states will exist as an authority Although states may not be able to control every situation, they may be able to act more quickly and decisively when their information is stolen. This risk may increase during car-sharing, and user data may be compromised. The attacker may gain access to the exterior or interior of the vehicle for long enough to carry out an attack or tamper with one or more vehicle systems so that an attack can be carried out later (Ward and Wooderson, 2021).

(2) Technology Aspect

C_4: Need for internet connection stability (cost): The 5G technology connection speed must be fast and stable because some problems may occur in the system if there are latencies, a lack of connection, or a failure in the internet connection. Beyond a 5G network with high mobility of 1000 km/h, which is 1000 times faster than 4G technology, it is possible to track and sense autonomous vehicles with high accuracy (Reebadiya et al., 2021). It is possible to control remotely autonomous heavy machinery using 5G. As a result, the internet connection must be extremely fast.

C_5: Available trained personnel (benefit): Expert drivers will be required in the case of the use of self-driving vehicles. The need for available trained personnel may be met by gamers who put on their VR glasses and drive their cars. Although

people may be trained to use it, there will be an advantage because there are many available gamers, making the process simple.

C_6: Providing technological compatibility of highway infrastructure (cost): Even though holograms appear and move in the car through a connection to the internet, the road must also be technologically ready for it. This infrastructure makes it safer for self-driving and electric vehicles to move around. One of these technologies is automated highways. It is a smart transportation system that uses technologies in cars and on roads to take over driving tasks from the driver and give them to the cars (Pandey, 2022). In the same way, the whole road needs to be updated to keep up with technological changes, which costs money.

(3) Social and Economic Aspect

C_7: Affordability issues (cost): Although the Metaverse will improve traffic safety by using holograms in cars, owning or using a car with hologram technology will incur some costs. The third option will be appropriate to make these cars available to the public, or to eliminate such a problem private companies may cover the expenses and solve cost problems through a large number of users. When it comes to states, they must invest in public transportation training. In the fourth option, perhaps the vehicle will be able to adapt to this system. That is, a hologram appearing in the vehicle and indicating hotspots and instructions on how to use it requires a certain amount of funds, which governments may not have readily available. As a result, in contrast to the disadvantages of the first and fourth alternatives, this problem may be addressed in the second and third alternatives. One example is the Istanbul Metropolitan Municipality, which has a system and simulators for psychological evaluations and points scoring with drivers (Istanbul Metropolitan Municipality, 2022). This infrastructure is already in place, but it must be brought into line with the Metaverse.

C_8: Social acceptance (benefit): Social acceptance is advantageous because it increases the likelihood that the alternative is preferable. The social acceptance of such technologies will be advantageous for the advancement of technology. As perceived usefulness and perceived ease of use shape users' attitudes toward technology use, factors such as self-efficiency, social norm, perceived curiosity, perceived pleasure, and price have a direct impact on the social acceptance process (Aburbeian et al., 2022). Consequently, societal behavioral attitudes may shift if the four alternatives are considered. Because hologram technology may provide users with satisfactory responses during the payment process and the delivery of their vehicles in the sharing economy, the third option may garner greater social acceptance.

C_9: Facilitating the lives of the elderly and disabled (benefit): The hologram technology will assist elderly or disabled drivers in controlling their vehicles, which will improve traffic safety. The vehicles will be equipped with artificial intelligence technology, an image processing unit, four motorized wheels, cameras, and microphones to recognize their surroundings. This will help elderly and disabled drivers maximize their quality of life (Hossain et al., 2021).

(4) Traffic Aspect

C_{10}: Optimized traffic flow (benefit): Because inexperienced drivers stop, get up, and/or slow down unnecessarily in traffic, the first option provides the most effective traffic flow optimization. These are the behaviors that prevent the optimization of traffic. Utilizing this criterion in the Metaverse optimizes traffic flow, making it more efficient and effective. In the second option, improper use of buses for public transportation is problematic. With such guidance, increasing training can be made more efficient. Some AI experiments indicate whether drivers of public transportation are fatigued or frustrated. International Association of Public Transport published a report on use-cases of AI applications in public transport and what the future may hold for AI, and PwC (PricewaterhouseCoopers) surveyed to determine the impact of AI on decision-makers and regular employees in a variety of public transportation-related industries (Iyer, 2021). These are the preliminary studies' experiments. Regarding the third option, when car rentals are made, the vehicles may be driven aggressively through unnecessary stop-and-go driving or improper passing, in this instance, AI applications could take overdriving thereby allowing traffic to flow smoothly. The purpose of the fourth alternative is to provide a little more traffic security so that enhanced traffic flow may not be immediately apparent.

C_{11}: Road accidents (cost): This can also be interpreted as an increase in road accidents that incurs costs. In terms of the first alternative, the accident rate may increase as a result of inexperienced motorists. In the second option, bus drivers can be prevented from misusing their vehicles, thereby avoiding accidents. In the third alternative, car-sharing can result in accidents due to poor vehicle usage. Because there is a hologram, this can be avoided, and people can now drive more precisely because they feel in control. Concerning this criterion, the fourth alternative may acquire importance because in the fourth alternative, drivers are correctly guided and warned as they approach hotspots. Because drivers are highly stimulated by visuals such as holograms, this option is essential to reduce road accidents.

C_{12}: Providing higher-quality traffic management (benefit): This criterion can be interpreted as improved traffic control. The authorities will get high-quality traffic control if they show the holograms to the drivers, manage them, and tell them directly what to do during traffic congestion.

4. Proposed methodology

Two segments representing separate modules in the decision-making model are implemented in the presented MCDM methodology (see Fig. 1).

The first module presents the improved fuzzy E-LMAW methodology, which was used to define the weighting coefficients of the criteria. In the second module, a novel methodology for evaluating alternatives is presented, which is based on the nonlinear processing of information based on nonlinear fuzzy Einstein weight functions (fuzzy Einstein TOPSIS). By applying nonlinear fuzzy Einstein functions, it is possible to adapt the methodological framework of the TOPSIS method to a dynamic environment. Therefore, the proposed methodology has advantages and novelties as follows: 1) Fuzzy Einstein TOPSIS method is based on nonlinear processing of the elements of the initial decision matrix with the possibility of considering different degrees of risk in a dynamic environment. This characteristic provides the possibility of flexible decision-making, which increases its generality and flexibility compared to the traditional TOPSIS method; 2) It is proposed to improve the traditional LMAW methodology based on nonlinear fuzzy Einstein functions, which enables the processing of uncertain and undetermined information. Also, the fuzzy E-LMAW methodology enables the definition of the weighting coefficients of criteria in conditions of incomplete information about specific attributes. 3) The proposed multi-criteria framework has a high degree of adaptability, enabling its application in other real problems and enabling flexible decision-making, whether group or individual.

In the following part, the methodological foundations of fuzzy Einstein norms are presented as well as the basic idea for their implementation in the proposed multi-criteria reasoning algorithm.

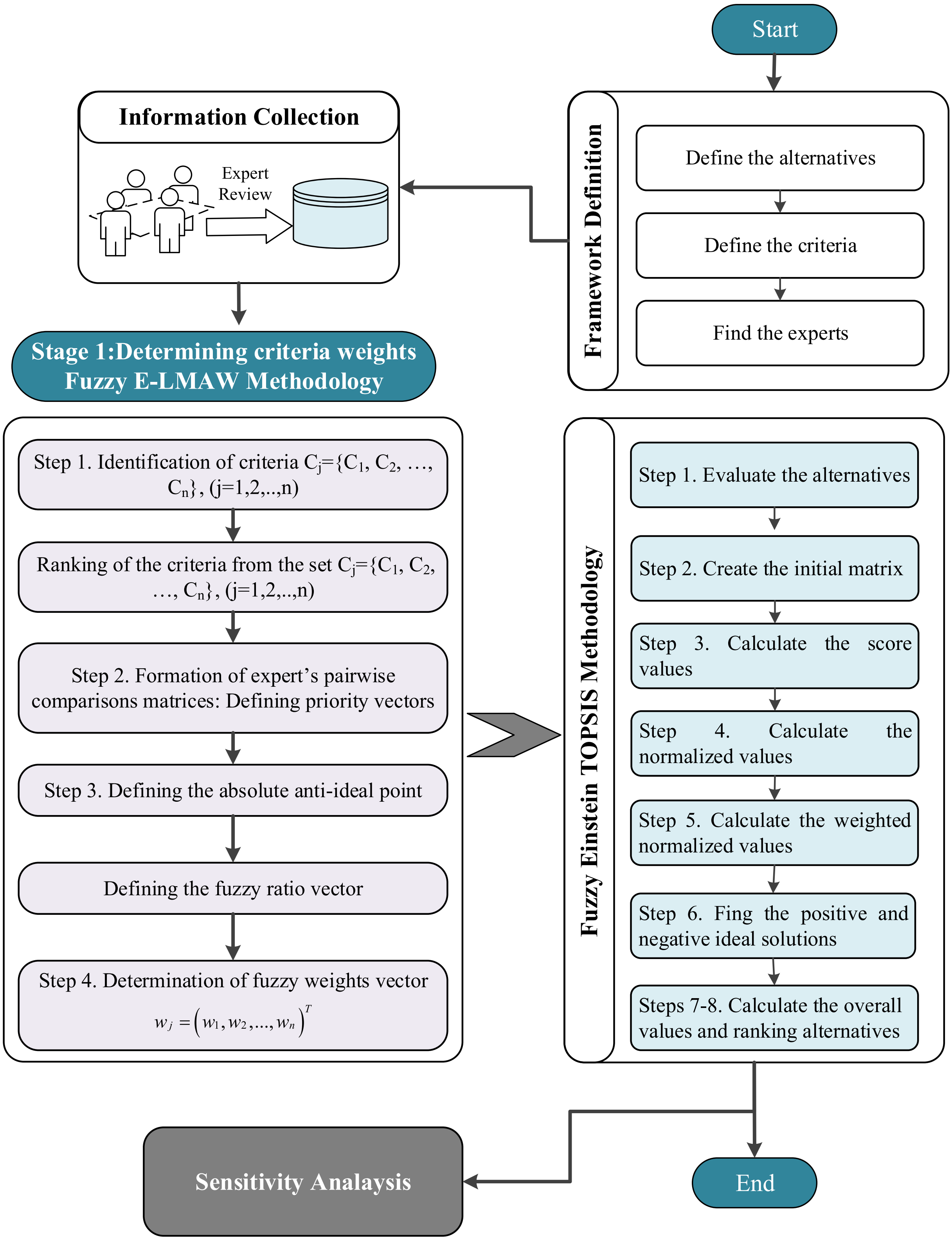

Fig. 1. The flowchart of the proposed methodology.

4.1. Fuzzy Einstein T-norms and T-conorms

Zadeh (1965) developed the fuzzy set theory to address uncertainties in the information. Triangular fuzzy numbers (TFNS) are used to handle uncertain information in this study. TFNs are described by the membership function $\rho_{\Re}(\mho)$: $R \rightarrow [0,1]$ as follows:

$$\rho_{\Re}(\mho)=\begin{cases}\dfrac{\mho-x}{z-x} & x\le\mho\le z\\ 1 & \mho=y\\ \dfrac{z-\mho}{z-y} & y\le\mho\le z\\ 0 & otherwise\end{cases} \tag{1}$$

where the lower and upper bounds of the fuzzy number J are denoted x and z, and y denotes the middle value for J.

Definition 1. Let $\mathfrak{I}_1$ and $\mathfrak{I}_2$ be two real fuzzy numbers in J. Then their norm and conorm of $\mathfrak{I}_1$ and $\mathfrak{I}_2$ are defined by (Hamachar, 1978):

$$t(\mathfrak{I}_1,\mathfrak{I}_2)=\frac{\mathfrak{I}_1\mathfrak{I}_2}{1+(1-\mathfrak{I}_1)(1-\mathfrak{I}_2)} \tag{2}$$

$$t^{con}(\mathfrak{I}_1,\mathfrak{I}_2)=\frac{\mathfrak{I}_1+\mathfrak{I}_2}{1+\mathfrak{I}_1\mathfrak{I}_2} \tag{3}$$

where $(\mathfrak{I}_1,\mathfrak{I}_2)\in[0,1]$.

Definition 2. Let$\mathfrak{I}_1=\left(\mathfrak{I}_1^{(x)},\mathfrak{I}_1^{(y)},\mathfrak{I}_1^{(z)}\right)$ and $\mathfrak{I}_2=\left(\mathfrak{I}_2^{(x)},\mathfrak{I}_2^{(y)},\mathfrak{I}_2^{(z)}\right)$ be two triangular fuzzy numbers (TFNs),

$f(\mathfrak{I}_i)=\left(f\left(\mathfrak{I}_i^{(x)}\right),f\left(\mathfrak{I}_i^{(y)}\right)f\left(\mathfrak{I}_i^{(z)}\right)\right)=\left(\mathfrak{I}_i^{(x)}/\sum_{i=1}^{n}\mathfrak{I}_i^{(x)},\mathfrak{I}_i^{(y)}/\sum_{i=1}^{n}\mathfrak{I}_i^{(y)},\mathfrak{I}_i^{(z)}/\sum_{i=1}^{n}\mathfrak{I}_i^{(z)},\right)$, then some basic concepts and operators of the Einstein T-norm and T-conorm under TFNs are introduced as follows:

(1) The addition of $\mathfrak{I}_1$ and $\mathfrak{I}_2$ can be expressed by:

$$\mathfrak{I}_1+\mathfrak{I}_2=\begin{pmatrix}\left(\mathfrak{I}_1^{(x)}+\mathfrak{I}_2^{(x)}\right)\dfrac{f\left(\mathfrak{I}_1^{(x)}\right)+f\left(\mathfrak{I}_2^{(a)}\right)}{1+f\left(\mathfrak{I}_1^{(x)}\right)f\left(\mathfrak{I}_2^{(x)}\right)},\\ \left(\mathfrak{I}_1^{(y)}+\mathfrak{I}_2^{(y)}\right)\dfrac{f\left(\mathfrak{I}_1^{(y)}\right)+f\left(\mathfrak{I}_2^{(y)}\right)}{1+f\left(\mathfrak{I}_1^{(y)}\right)f\left(\mathfrak{I}_2^{(y)}\right)},\\ \left(\mathfrak{I}_1^{(z)}+\mathfrak{I}_2^{(z)}\right)\dfrac{f\left(\mathfrak{I}_1^{(z)}\right)+f\left(\mathfrak{I}_2^{(z)}\right)}{1+f\left(\mathfrak{I}_1^{(z)}\right)f\left(\mathfrak{I}_2^{(z)}\right)}\end{pmatrix} \tag{4}$$

(2) The multiplication of $\mathfrak{I}_1$ and $\mathfrak{I}_2$ can be expressed by:

$$\mathfrak{I}_1\times\mathfrak{I}_2=\begin{pmatrix}\left(\mathfrak{I}_1^{(x)}+\mathfrak{I}_2^{(x)}\right)\dfrac{f\left(\mathfrak{I}_1^{(x)}\right)f\left(\mathfrak{I}_2^{(x)}\right)}{1+\left(1-f\left(\mathfrak{I}_1^{(x)}\right)\right)\left(1-f\left(\mathfrak{I}_1^{(x)}\right)\right)},\\ \left(\mathfrak{I}_1^{(y)}+\mathfrak{I}_2^{(y)}\right)\dfrac{f\left(\mathfrak{I}_1^{(y)}\right)f\left(\mathfrak{I}_2^{(y)}\right)}{1+\left(1-f\left(\mathfrak{I}_1^{(y)}\right)\right)\left(1-f\left(\mathfrak{I}_1^{(y)}\right)\right)},\\ \left(\mathfrak{I}_1^{(z)}+\mathfrak{I}_2^{(z)}\right)\dfrac{f\left(\mathfrak{I}_1^{(z)}\right)f\left(\mathfrak{I}_2^{(z)}\right)}{1+\left(1-f\left(\mathfrak{I}_1^{(z)}\right)\right)\left(1-f\left(\mathfrak{I}_1^{(z)}\right)\right)}\end{pmatrix} \tag{5}$$

(3) Scalar multiplication, where $\psi>0$

$$\psi\mathfrak{I}_1=\begin{pmatrix}\mathfrak{I}_1^{(x)}\dfrac{\left(1+f\left(\mathfrak{I}_1^{(x)}\right)\right)^{\psi}-\left(1-f\left(\mathfrak{I}_1^{(x)}\right)\right)^{\psi}}{\left(1+f\left(\mathfrak{I}_1^{(x)}\right)\right)^{\psi}+\left(1-f\left(\mathfrak{I}_1^{(x)}\right)\right)^{\psi}},\\ \mathfrak{I}_1^{(y)}\dfrac{\left(1+f\left(\mathfrak{I}_1^{(y)}\right)\right)^{\psi}-\left(1-f\left(\mathfrak{I}_1^{(y)}\right)\right)^{\psi}}{\left(1+f\left(\mathfrak{I}_1^{(y)}\right)\right)^{\psi}+\left(1-f\left(\mathfrak{I}_1^{(y)}\right)\right)^{\psi}},\\ \mathfrak{I}_1^{(z)}\dfrac{\left(1+f\left(\mathfrak{I}_1^{(z)}\right)\right)^{\psi}-\left(1-f\left(\mathfrak{I}_1^{(z)}\right)\right)^{\psi}}{\left(1+f\left(\mathfrak{I}_1^{(z)}\right)\right)^{\psi}+\left(1-f\left(\mathfrak{I}_1^{(z)}\right)\right)^{\psi}}\end{pmatrix} \tag{6}$$

(4) Power, where $\psi>0$

$$\mathfrak{I}_1^{\psi}=\begin{pmatrix}\mathfrak{I}_1^{(x)}\dfrac{2f\left(\mathfrak{I}_1^{(x)}\right)^{\psi}}{\left(2-f\left(\mathfrak{I}_1^{(x)}\right)\right)^{\psi}+f\left(\mathfrak{I}_1^{(x)}\right)^{\psi}},\\ \mathfrak{I}_1^{(y)}\dfrac{2f\left(\mathfrak{I}_1^{(y)}\right)^{\psi}}{\left(2-f\left(\mathfrak{I}_1^{(y)}\right)\right)^{\psi}+f\left(\mathfrak{I}_1^{(y)}\right)^{\psi}},\\ \mathfrak{I}_1^{(z)}\dfrac{2f\left(\mathfrak{I}_1^{(z)}\right)^{\psi}}{\left(2-f\left(\mathfrak{I}_1^{(z)}\right)\right)^{\psi}+f\left(\mathfrak{I}_1^{(z)}\right)^{\psi}}\end{pmatrix} \tag{7}$$

Definition 3. Let $\mathfrak{I}_j=\left(\mathfrak{I}_j^{(x)},\mathfrak{I}_j^{(y)},\mathfrak{I}_j^{(z)}\right)(j=1,2,\ldots,m)$ be a set of TFNs, and $\mathbb{C}=(\mathbb{C}_1,\mathbb{C}_2,\ldots,\mathbb{C}_m)$ $\mathbb{C}_j\in[0,1]$ be the weight coefficient of $\mathfrak{I}_j=\left(\mathfrak{I}_j^{(x)},\mathfrak{I}_j^{(y)},\mathfrak{I}_j^{(z)}\right)(j=1,2,\ldots,m)$ with condition that $\sum_{j=1}^{m}\mathbb{C}_j=1$. Then, the fuzzy weighted averaging (FWA) operator and fuzzy weighted geometric averaging (FWGA) operator are as expressed by (Ali et al., 2021; Youssef and Webster, 2022):

$$\begin{aligned}FWA(\mathfrak{I}_1,\mathfrak{I}_2,..,\mathfrak{I}_m)&=\sum_{j=1}^{m}\mathbb{C}_j\mathfrak{I}_j\\&=\left(\sum_{j=1}^{m}\mathbb{C}_j^{(x)}\mathfrak{I}_j^{(x)},\sum_{j=1}^{m}\mathbb{C}_j^{(y)}\mathfrak{I}_j^{(y)},\sum_{j=1}^{m}\mathbb{C}_j^{(z)}\mathfrak{I}_j^{(z)}\right)\end{aligned} \tag{8}$$

$$\begin{aligned}FWGA(\mathfrak{I}_1,\mathfrak{I}_2,..,\mathfrak{I}_m)&=\prod_{j=1}^{m}(\mathfrak{I}_j)^{\psi_j}\\&=\left(\prod_{j=1}^{m}\left(\mathfrak{I}_j^{(x)}\right)^{\psi_j^{(x)}},\prod_{j=1}^{m}\left(\mathfrak{I}_j^{(y)}\right)^{\psi_j^{(y)}},\prod_{j=1}^{m}\left(\mathfrak{I}_j^{(z)}\right)^{\psi_j^{(z)}}\right)\end{aligned} \tag{9}$$

4.2. Determining criteria weights

This section presents an improvement of the traditional Logarithmic Methodology of Additive Weights (LMAW) introduced by Pamucar et al. (2021). The improvement of the LMAW methodology is based on the implementation of Einstein norms, which eliminate the lack of classic min-max operators in the fuzzy environment Zadeh (1965). Earlier research presented by Zadeh (1965) recommends the application of algebraic operators that satisfy all axiomatic properties, thereby eliminating the limitations of traditional min-max operators. Therefore, the authors decided to implement Einstein operators (Hamachar, 1978) in this study. Applying the Einstein norm eliminates the following limitations of traditional min-max operators: 1) eliminates the property that the result is determined by only one variable, and 2) min-max operators are not analytical, and their second derivative is not continuous. Also, according to Fahmi et al., (2018), mathematical operators based on Einstein's norms model everyday human reasoning well and have the effect of improving the elasticity of decision-making models.

The advanced fuzzy Einstein LMAW (fuzzy E-LMAW) methodology is based on defining the relationship between criteria using a logarithmic function. Applying the Einstein norms improves the performance of the traditional LMAW through the appreciation of mutual relations between the criteria and flexible decision-making due to decision makers' risk attitude. In the following part, the mathematical performances of the fuzzy E-LMAW methodology are presented. The steps of this model are also shown in Fig. 1.

Step 1. Determining the fuzzy priority vector. Using a predefined fuzzy scale, experts present their preferences according to the significance of the criteria. Thus, for each expert, we get a priority vector $\Re^b = \left(\widetilde{\wp}^b_{C_1}, \widetilde{\wp}^b_{C_2}, .., \widetilde{\wp}^b_{C_n}\right)$, where $\widetilde{\wp}^b_{C_1}$ represents the fuzzy assessment that the expert b assigned to criterion C_1.

Step 2. The significance of the criteria is defined in relation to the absolute anti-ideal point (υ_{AIP}), which is defined using Eq. (10)

$$\upsilon_{AIP} < \min_{1\le k\le h}(\widetilde{\wp}_k) \tag{10}$$

where $\widetilde{\wp}_k$ represents the value from the predefined fuzzy scale, while h represents the total number of elements in the fuzzy scale.

Step 3. Applying Eq. (11) defines the ratio vector $\mathfrak{I}^b = \left(\widetilde{\partial}^b_{C_1}, \widetilde{\partial}^b_{C_2}, .., \widetilde{\partial}^b_{C_n}\right)$. The ratio vector ($\upsilon_{AIP}$) represents as follows:

$$\widetilde{\zeta}^b_{C_j} = \frac{\widetilde{\wp}^b_{C_j}}{\upsilon_{AIP}} \tag{11}$$

where $\widetilde{\wp}^b_{C_j} \in \Re^b$ and $\widetilde{\wp}^b_{C_j} = \left(\wp^{(l)b}_{C_j}, \wp^{(m)b}_{C_j}, \wp^{(u)b}_{C_j}\right)$.

Step 4. Defining the final fuzzy vector of weight coefficients $\widetilde{w}_j = (\widetilde{w}_1, \widetilde{w}_2, \ldots, \widetilde{w}_n)^T$. Applying Eq. (12), we get the weighting coefficients of the criteria for each expert individually.

$$\widetilde{w}^b_j = \frac{\ln\left(\widetilde{\zeta}^b_{C_j}\right)}{\ln\left(\widetilde{\rho}^b_j\right)} \tag{12}$$

where

$$\widetilde{\rho}^b_j = \left(\rho^{(l)b}_j, \rho^{(m)b}_j, \rho^{(u)b}_j\right)$$

$$= \begin{cases} \rho^{(l)b}_j = \sum_{j=1}^{n} \zeta^{(l)b}_{C_j} \dfrac{\phi \prod_{j=1}^{n} f\left(\zeta^{(l)b}_{C_j}\right)^{\alpha}}{\prod_{j=1}^{n}\left(1+(\phi-1)\left(1-f\left(\zeta^{(l)b}_{C_j}\right)\right)\right)^{\alpha}+(\phi-1)\prod_{j=1}^{n} f\left(\zeta^{(l)b}_{C_j}\right)^{\alpha}}, \\ \rho^{(m)b}_j = \sum_{j=1}^{n} \zeta^{(m)b}_{C_j} \dfrac{\phi \prod_{j=1}^{n} f\left(\zeta^{(m)b}_{C_j}\right)^{\alpha}}{\prod_{j=1}^{n}\left(1+(\phi-1)\left(1-f\left(\zeta^{(m)b}_{C_j}\right)\right)\right)^{\alpha}+(\phi-1)\prod_{j=1}^{n} f\left(\zeta^{(m)b}_{C_j}\right)^{\alpha}}, \\ \rho^{(u)b}_j = \sum_{j=1}^{n} \zeta^{(u)b}_{C_j} \dfrac{\phi \prod_{j=1}^{n} f\left(\zeta^{(u)b}_{C_j}\right)^{\alpha}}{\prod_{j=1}^{n}\left(1+(\phi-1)\left(1-f\left(\zeta^{(u)b}_{C_j}\right)\right)\right)^{\alpha}+(\phi-1)\prod_{j=1}^{n} f\left(\zeta^{(u)b}_{C_j}\right)^{\alpha}} \end{cases} \tag{13}$$

where $\phi = 2$, and $f\left(\widetilde{\zeta}^b_{C_j}\right) = \left(\zeta^{(l)b}_{C_j}/\sum_{i=1}^{n}\zeta^{(l)b}_{C_j}, \zeta^{(m)b}_{C_j}/\sum_{i=1}^{n}\zeta^{(m)b}_{C_j}, \zeta^{(u)b}_{C_j}/\sum_{i=1}^{n}\zeta^{(u)b}_{C_j}\right)$.

The final fuzzy vector of weight coefficients is obtained by applying the expression (14):

$$w_j = \left(w_j^{(l)}, w_j^{(m)}, w_j^{(u)}\right) =$$

$$= \begin{cases} w_j^{(l)} = \sum_{b=1}^{k} w_j^{(l)b} \dfrac{\prod_{b=1}^{k}\left(1+(\phi-1)f\left(w_j^{(l)b}\right)\right)^{1/k} - \prod_{b=1}^{k}\left(1-f\left(w_j^{(l)b}\right)\right)^{1/k}}{\prod_{b=1}^{k}\left(1+(\phi-1)f\left(w_j^{(l)b}\right)\right)^{1/k} + (\phi-1)\prod_{b=1}^{k}\left(1-f\left(w_j^{(l)b}\right)\right)^{1/k}}, \\ w_j^{(m)} = \sum_{b=1}^{k} w_j^{(m)b} \dfrac{\prod_{b=1}^{k}\left(1+(\phi-1)f\left(w_j^{(m)b}\right)\right)^{1/k} - \prod_{b=1}^{k}\left(1-f\left(w_j^{(m)b}\right)\right)^{1/k}}{\prod_{b=1}^{k}\left(1+(\phi-1)f\left(w_j^{(m)b}\right)\right)^{1/k} + (\phi-1)\prod_{b=1}^{k}\left(1-f\left(w_j^{(m)b}\right)\right)^{1/k}}, \\ w_j^{(u)} = \sum_{b=1}^{k} w_j^{(u)b} \dfrac{\prod_{b=1}^{k}\left(1+(\phi-1)f\left(w_j^{(u)b}\right)\right)^{1/k} - \prod_{b=1}^{k}\left(1-f\left(w_j^{(u)b}\right)\right)^{1/k}}{\prod_{b=1}^{k}\left(1+(\phi-1)f\left(w_j^{(u)b}\right)\right)^{1/k} + (\phi-1)\prod_{b=1}^{k}\left(1-f\left(w_j^{(u)b}\right)\right)^{1/k}} \end{cases} \tag{14}$$

where $\phi = 2$, $f\left(\widetilde{w}^b_j\right) = \left(w_j^{(l)b}/\sum_{b=1}^{k} w_j^{(l)b}, w_j^{(m)b}/\sum_{b=1}^{k} w_j^{(m)b}, w_j^{(u)b}/\sum_{b=1}^{k} w_j^{(u)b}\right)$, and k represent a number of experts.

4.3. Fuzzy Einstein TOPSIS model

The TOPSIS method was introduced by Hwang and Yoon (1981) as a mathematical tool to solve the MCDM problems, and to cope with uncertainty such as vagueness and imprecision in the information (Nazim et al., 2022). The framework of the proposed model is presented in Fig. 1.

Let $\aleph_i = (\aleph_1, \aleph_2, \cdots \aleph_n)(i = 1, 2, \cdots, n)$ be an alternative set, $\mathbb{Q}_j = (\mathbb{Q}_1, \mathbb{Q}_2, \cdots \mathbb{Q}_m)(j = 1, 2, \cdots, m)$ be a criterion set, and $\mathbb{Z}_l = (\mathbb{Z}_1, \mathbb{Z}_2, \cdots \mathbb{Z}_e)(l = 1, 2, \cdots, e)$ be an expert set. The fuzzy Einstein TOPSIS model includes the following steps:

Step 1. Each alternative is rated by e experts regarding m decision criteria using a fuzzy scale. An initial decision matrix $\eta^{\ell} = \left[\partial_{ij}^{\ell}\right]_{n\times m}(1 \le \ell \le e)$ is built for each expert $\mathbb{Z}_l(1 \le \ell \le e)$. The initial matrix η^{ℓ} is transformed into fuzzy values $\widetilde{\partial}_{ij}^{\ell} = \left(\partial_{ij}^{(x)\ell}, \partial_{ij}^{(y)\ell}, \partial_{ij}^{(z)\ell}\right)$ using a fuzzy linguistic scale.

Step 2. Later, the individual decision matrices with respect to experts' opinions are aggregated in one aggregated decision matrix $A = \left[\zeta_{ij}\right]_{n\times m}$ is calculated using the fuzzy Einstein weighted average (FEWAA) operator as given in Eq. (15) (Hamachar, 1978).

$$\zeta_j = \left(\zeta_i^{(x)}, \zeta_i^{(y)}, \zeta_i^{(z)}\right)$$

$$= \begin{pmatrix} \sum_{j=1}^{e}\left(\tau_{ij}^{(x)\ell}\right)\dfrac{\prod_{j=1}^{e}\left(1+f\left(\tau_{ij}^{(x)\ell}\right)\right)^{1/e} - \prod_{j=1}^{e}\left(1-f\left(\tau_{ij}^{(x)\ell}\right)\right)^{1/e}}{\prod_{j=1}^{e}\left(1+f\left(\tau_{ij}^{(x)\ell}\right)\right)^{1/e} + \prod_{j=1}^{e}\left(1-f\left(\tau_{ij}^{(x)\ell}\right)\right)^{1/e}}, \\ \sum_{j=1}^{e}\left(\tau_{ij}^{(y)\ell}\right)\dfrac{\prod_{j=1}^{e}\left(1+f\left(\tau_{ij}^{(y)\ell}\right)\right)^{1/e} - \prod_{j=1}^{e}\left(1-f\left(\tau_{ij}^{(y)\ell}\right)\right)^{1/e}}{\prod_{j=1}^{e}\left(1+f\left(\tau_{ij}^{(y)\ell}\right)\right)^{1/e} + \prod_{j=1}^{e}\left(1-f\left(\tau_{ij}^{(y)\ell}\right)\right)^{1/e}}, \\ \sum_{j=1}^{e}\left(\tau_{ij}^{(z)\ell}\right)\dfrac{\prod_{j=1}^{e}\left(1+f\left(\tau_{ij}^{(z)\ell}\right)\right)^{1/e} - \prod_{j=1}^{e}\left(1-f\left(\tau_{ij}^{(z)\ell}\right)\right)^{1/e}}{\prod_{j=1}^{e}\left(1+f\left(\tau_{ij}^{(z)\ell}\right)\right)^{1/e} + \prod_{j=1}^{e}\left(1-f\left(\tau_{ij}^{(z)\ell}\right)\right)^{1/e}} \end{pmatrix} \tag{15}$$

Step 3. In this step, decision matrices of $\zeta_i$are aggregated using the score function by Eq. (16):

$$\vartheta_{ij} = \left(\frac{\zeta_{ij}^{(x)} + 4\zeta_{ij}^{(y)} + \zeta_{ij}^{(z)}}{6}\right) \tag{16}$$

Step 4. The decision matrix $A = \left[\zeta_{ij}\right]_{n\times m}$ is normalized according to the type of criteria (Benefit and Cost) with the help of Eq. (17):

$$\varphi_{ij} = \left(\varphi_{ij}^{(x)}, \varphi_{ij}^{(y)}, \varphi_{ij}^{(z)}\right) = \begin{cases} \varphi_{ij}^{(x)} = \dfrac{\zeta_{ij}^{(x)}}{\zeta_j^{+}}; \varphi_{ij}^{(b)} = \dfrac{\zeta_{ij}^{(y)}}{\zeta_j^{+}}; \varphi_{ij}^{(c)} = \dfrac{\zeta_{ij}^{(z)}}{\zeta_j^{+}} & if \quad j \in B, \\ \varphi_{ij}^{(x)} = \dfrac{\zeta_j^{-}}{\zeta_{ij}^{(x)}}; \varphi_{ij}^{(b)} = \dfrac{\zeta_j^{-}}{\zeta_{ij}^{(y)}}; \varphi_{ij}^{(c)} = \dfrac{\zeta_j^{-}}{\zeta_{ij}^{(z)}} & if \quad j \in C. \end{cases} \tag{17}$$

where the element of the normalized decision matrix is represented by $N = \left[\varphi_{ij}\right]_{n\times m}$.

The elements $\varphi_j^{-}$and φ_j^{+} are found by:

$$\varphi_j^{-} = \min_{i \le j \le m}\left(\varphi_{ij}\right) \tag{18}$$

$$\varphi_j^{+} = \max_{i \le j \le m}\left(\varphi_{ij}\right) \tag{19}$$

Step 5. Calculate the weighted normalized matrix $V = \left[\nu_{ij}\right]_{n\times m}$using the weights of criteria as follows:

$$V = \nu_{ij} \times w_j \tag{20}$$

Step 6. Find the positive ideal (Δ^{+}) and negative ideal (Δ^{-}) solutions.

$$v_j^{-} = \min_{i \le j \le m}\left(v_{ij}\right) \quad if \quad \text{Cost} \tag{21}$$

$$v_j^{+} = \max_{i \le j \le m}\left(v_{ij}\right) \quad if \quad Benefit \tag{22}$$

$$\begin{cases} \Delta_i^{+} = \sqrt{\sum\left(v_{ij} - v_j^{+}\right)^2}; & if \quad j \in B, \\ \Delta_i^{+} = \sqrt{\sum\left(v_{ij} - v_j^{-}\right)^2}; & if \quad j \in C. \end{cases} \tag{23}$$

where v_j^{-} and v_j^{+} represent max and min values of the weighted normalized values for each criterion.

Step 7. Determine the closeness coefficient (α_i) of each alternative as follow:

$$\alpha_i = \frac{\Delta^{-}}{\Delta^{-} + \Delta^{+}} \tag{24}$$

Step 8. Finally, alternatives are ranked according to their α_i score values.

5. Case study

The benefits of recent technology, such as the Metaverse, will be unavoidable soon, and its implementation will be required. There may be many cases where some alternatives are evaluated and prioritized. In an imaginary city where technology applications must be implemented and decision-makers aim to use the Metaverse's potential in traffic safety. This city's education level and population rate may be both high.

Four alternatives, each with four aspects and twelve criteria, provide a detailed method for integrating the Metaverse and traffic safety. In fact, it may be difficult to implement alternatives and provide social acceptance in cities with diverse characteristics, which may result in a limitation. As a result, these alternatives can be tailored to those cities. As the Metaverse's capabilities expand, so will the number and applicability of alternatives.

The majority of the individuals consulted for this study have extensive experience in the creation of video games, the implementation of transactional systems in the Metaverse that make use of blockchain technology, as well as management and traffic control. In addition, a few of the experts have previous experience working within the realm of virtual reality (VR) technology. As a result, these industry professionals have the opportunity to conduct an in-depth understanding of the advantages and disadvantages associated with a variety of applications available in the Metaverse, such as the alternatives to this study. Because of this, the reliability of the results of the advantage prioritization given in the section containing the results and discussion is increased.

5.1. Application of fuzzy E-LMAW methodology for determining weight coefficients

The criteria are grouped into four clusters within which twelve criteria are distributed, as reported in Table 1. The clusters are coded MC_1 - Rules and Regulations Aspect, MC_2 - Technology Aspect, MC_3 - Social and Economic Aspect, and MC_4 - Urban Sustainability and Livability Aspect. Codes from C_1 to C_{12} were used to mark the criteria within the cluster.

In the following part, the fuzzy E-LMAW methodology's application for determining the criteria's weighting coefficients is presented. Global values of weight coefficients are defined within each hierarchical level separately.

Table 1
The hierarchy of the evaluation criteria.

Main-criteria	Sub-criteria	Types
Rules and Regulations Aspect (MC_1)		
C_1	Privacy concerns	Cost
C_2	Challenges in interoperability across platforms, devices, and jurisdictions	Cost
C_3	Concerns and challenges relating to cybersecurity	Cost
Technology Aspect (MC_2)		
C_4	Need for Internet connection stability	Cost
C_5	Available trained personnel	Benefit
C_6	Providing technological compatibility of highway infrastructure	Cost
Social and Economic Aspect (MC_3)		
C_7	Affordability issues	Cost
C_8	Social acceptance	Benefit
C_9	Facilitating the lives of the elderly and disabled	Cost
Urban Sustainability and Livability Aspect (MC_4)		
C_{10}	Optimized traffic flow	Benefit
C_{11}	Road accidents	Cost
C_{12}	Providing higher quality traffic management (control)	Benefit

Table 2
Fuzzy scale for evaluating criteria and alternatives (Rakhmangulov et al., 2019).

Linguistic terms	Membership function
Absolutely low (AL)	(1, 1, 1)
Very low (VL)	(1, 2, 3)
Low (L)	(2, 3, 4)
Medium low (ML)	(3, 4, 5)
Equal (E)	(4, 5, 6)
Medium high (MH)	(5, 6, 7)
High (H)	(6, 7, 8)
Very high (VH)	(7, 8, 9)
Absolutely high (AH)	(8, 9, 9)

Step 1: Six experts evaluated the criteria using a fuzzy scale, as given in Table 2.

The experts presented the significance of the criteria within the priority vectors of the criteria in Table 3.

Steps 2 and 3: Relationship vectors are defined by applying Eq. (11) with the help of Table 3. The ratio vector represents the ratio between the priority vector and the absolute anti-ideal point (AIP). In this research, AIP was adopted based on condition (10), that is, $\upsilon_{AIP} = (0.4, 0.5, 0.6)$ was adopted.

A relationship vector is defined based on AIP and the criteria's priority vector. For example, the relationship vector for the first cluster expert (MC_1–MC_4) is defined using Eq. (11) as follows:

Table 3
Criteria priority vectors.

Crit.	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
MC_1	E	H	H	VH	VH	H
MC_2	VH	VH	H	MH	AH	H
MC_3	H	AH	AH	MH	H	VH
MC_4	AH	VH	VH	H	MH	VH
Rules and Regulations Aspect (MC1)						
C_1	VH	AH	VH	VH	VH	VH
C_2	E	H	H	MH	H	MH
C_3	VH	VH	MH	VH	AH	H
Technology Aspect (MC2)						
C_4	H	AH	MH	E	AH	H
C_5	E	H	H	E	E	MH
C_6	VH	VH	VH	H	VH	VH
Social and Economic Aspect (MC3)						
C_7	H	AH	VH	VH	MH	VH
C_8	E	MH	H	MH	H	H
C_9	L	MH	MH	ML	ML	ML
Urban Sustainability and Livability Aspect (MC4)						
C_{10}	AH	VH	VH	VH	E	AH
C_{11}	VH	AH	H	AH	VH	AH
C_{12}	VH	H	H	VH	H	VH

$$\tilde{\zeta}^1_{MC_1} = \frac{(4,5,6)}{(0.4,0.5,0.6)} = (6.67,10,15);\ \tilde{\zeta}^1_{MC_2} = \frac{(7,8,9)}{(0.4,0.5,0.6)} = (11.67,16,22.5);$$

$$\tilde{\zeta}^1_{MC_3} = \frac{(6,7,8)}{(0.4,0.5,0.6)} = (10,14,20);\ \tilde{\zeta}^1_{MC_4} = \frac{(8,9,9)}{(0.4,0.5,0.6)} = (13.33,18,22.5).$$

The remaining elements of the criteria priority vector from Table 4 are defined similarly.

Step 4: By applying Eq. (12), the global values of the weighting coefficients of the criteria by expert groups were defined in Table 5.

The weight coefficient of the criterion MC_1 for the first expert is defined by applying Eq. (12):

$$\tilde{w}^1_{MC_1} = \frac{ln(6.67,10,15)}{ln(10370.37,40320,151875)} = (0.159,0.217,0.293)$$

where $ln\left(\tilde{\zeta}^b_{MC_1}\right) = ln(6.67,10,15)$ represents the element of the criteria priority vector, while $ln\left(\tilde{\rho}^1_{MC}\right) = ln(10370.37,40320,151875)$ we get by applying Eq. (13).

Aggregation of global vectors from Table 5 was performed using Eq. (14). The final values of the weight coefficients of the criteria are given in Table 6.

The aggregated fuzzy values of the weighting coefficients of the criteria are defined by applying Eq. (14), and with the condition that the weighting coefficients are the same for all experts, i.e. $w_b = 1/6 = 0.167$. In the following part, the aggregation of the left fuzzy value $w_{MC1}{}^{(l)}$ of the criteria $\tilde{w}_{MC1} = \left(w_{MC1}{}^{(l)}, w_{MC1}{}^{(m)}, w_{MC1}{}^{(u)}\right)$ is presented:

$$w_{MC1}{}^{(l)} = \begin{pmatrix} 0.159+0.487+0.188 \\ +0.208+0.203+0.188 \end{pmatrix} \frac{\begin{pmatrix} (1+(1-1)0.14)^{0.17}\cdot(1+(1-1)0.16)^{0.17}\cdot \\ (1+(1-1)0.17)^{0.17}\cdot\ldots\cdot(1+(1-1)0.17)^{0.17} \end{pmatrix} - \begin{pmatrix} (1-0.14)^{0.17}\cdot(1-0.16)^{0.17}\cdot \\ (1-0.17)^{0.17}\cdot\ldots\cdot(1-0.17)^{0.17} \end{pmatrix}}{\left(\begin{pmatrix} (1+(1-1)0.14)^{0.17}\cdot(1+(1-1)0.16)^{0.17}\cdot \\ (1+(1-1)0.17)^{0.17}\cdot\ldots\cdot(1+(1-1)0.17)^{0.17} \end{pmatrix}\right) + (1-1)\begin{pmatrix} (1-0.14)^{0.17}\cdot(1-0.16)^{0.17}\cdot \\ (1-0.17)^{0.17}\cdot\ldots\cdot(1-0.17)^{0.17} \end{pmatrix}} = 0.1890$$

Table 4
Criteria ratio vectors.

Crit.	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
MC_1	(6.67,10,15)	(10,14,20)	(10,14,20)	(11.67,16,22.5)	(11.67,16,22.5)	(10,14,20)
MC_2	(11.67,16,22.5)	(11.67,16,22.5)	(10,14,20)	(8.33,12,17.5)	(13.33,18,22.5)	(10,14,20)
MC_3	(10,14,20)	(13.33,18,22.5)	(13.33,18,22.5)	(8.33,12,17.5)	(10,14,20)	(11.67,16,22.5)
MC_4	(13.33,18,22.5)	(11.67,16,22.5)	(11.67,16,22.5)	(10,14,20)	(8.33,12,17.5)	(11.67,16,22.5)
Rules and Regulations Aspect (MC1)						
C_1	(11.67,16,22.5)	(13.33,18,22.5)	(11.67,16,22.5)	(11.67,16,22.5)	(11.67,16,22.5)	(11.67,16,22.5)
C_2	(6.67,10,15)	(10,14,20)	(10,14,20)	(8.33,12,17.5)	(10,14,20)	(8.33,12,17.5)
C_3	(11.67,16,22.5)	(11.67,16,22.5)	(8.33,12,17.5)	(11.67,16,22.5)	(13.33,18,22.5)	(10,14,20)
Technology Aspect (MC2)						
C_4	(10,14,20)	(13.33,18,22.5)	(8.33,12,17.5)	(6.67,10,15)	(13.33,18,22.5)	(10,14,20)
C_5	(6.67,10,15)	(10,14,20)	(10,14,20)	(6.67,10,15)	(6.67,10,15)	(8.33,12,17.5)
C_6	(11.67,16,22.5)	(11.67,16,22.5)	(11.67,16,22.5)	(10,14,20)	(11.67,16,22.5)	(11.67,16,22.5)
Social and Economic Aspect (MC3)						
C_7	(10,14,20)	(13.33,18,22.5)	(11.67,16,22.5)	(11.67,16,22.5)	(8.33,12,17.5)	(11.67,16,22.5)
C_8	(6.67,10,15)	(8.33,12,17.5)	(10,14,20)	(8.33,12,17.5)	(10,14,20)	(10,14,20)
C_9	(3.33,6,10)	(8.33,12,17.5)	(8.33,12,17.5)	(5,8,12.5)	(5,8,12.5)	(5,8,12.5)
Urban Sustainability and Livability Aspect (MC4)						
C_{10}	(13.33,18,22.5)	(11.67,16,22.5)	(11.67,16,22.5)	(11.67,16,22.5)	(6.67,10,15)	(13.33,18,22.5)
C_{11}	(11.67,16,22.5)	(13.33,18,22.5)	(10,14,20)	(13.33,18,22.5)	(11.67,16,22.5)	(13.33,18,22.5)
C_{12}	(11.67,16,22.5)	(10,14,20)	(10,14,20)	(11.67,16,22.5)	(10,14,20)	(11.67,16,22.5)

Table 5
Global vectors of weight coefficients within expert groups.

Crit.	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
MC_1	(0.159,0.217,0.293)	(0.187,0.238,0.305)	(0.188,0.241,0.310)	(0.208,0.267,0.346)	(0.203,0.257,0.329)	(0.188,0.244,0.315)
MC_2	(0.206,0.261,0.337)	(0.199,0.250,0.318)	(0.188,0.241,0.310)	(0.179,0.239,0.318)	(0.214,0.268,0.329)	(0.188,0.244,0.315)
MC_3	(0.193,0.249,0.324)	(0.210,0.261,0.318)	(0.212,0.264,0.323)	(0.179,0.239,0.318)	(0.191,0.245,0.316)	(0.201,0.256,0.327)
MC_4	(0.217,0.273,0.337)	(0.199,0.250,0.318)	(0.201,0.253,0.323)	(0.195,0.254,0.333)	(0.175,0.230,0.302)	(0.201,0.256,0.327)
Rules and Regulations Aspect (MC1)						
C_1	(0.275,0.353,0.457)	(0.281,0.348,0.424)	(0.274,0.351,0.453)	(0.270,0.345,0.443)	(0.266,0.334,0.424)	(0.274,0.351,0.453)
C_2	(0.212,0.293,0.398)	(0.250,0.318,0.408)	(0.257,0.334,0.435)	(0.233,0.309,0.407)	(0.250,0.318,0.408)	(0.236,0.315,0.416)
C_3	(0.275,0.353,0.457)	(0.266,0.334,0.424)	(0.236,0.315,0.416)	(0.270,0.345,0.443)	(0.281,0.348,0.424)	(0.257,0.334,0.435)
Technology Aspect (MC2)						
C_4	(0.261,0.342,0.450)	(0.281,0.348,0.424)	(0.236,0.315,0.416)	(0.226,0.318,0.444)	(0.290,0.363,0.448)	(0.257,0.334,0.435)
C_5	(0.215,0.298,0.407)	(0.250,0.318,0.408)	(0.257,0.334,0.435)	(0.226,0.318,0.444)	(0.212,0.289,0.390)	(0.236,0.315,0.416)
C_6	(0.279,0.359,0.468)	(0.266,0.334,0.424)	(0.274,0.351,0.453)	(0.274,0.364,0.491)	(0.275,0.348,0.448)	(0.274,0.351,0.453)
Social and Economic Aspect (MC3)						
C_7	(0.288,0.392,0.554)	(0.293,0.368,0.456)	(0.274,0.351,0.453)	(0.289,0.378,0.503)	(0.253,0.345,0.474)	(0.285,0.370,0.489)
C_8	(0.237,0.342,0.501)	(0.240,0.316,0.419)	(0.257,0.334,0.435)	(0.249,0.339,0.463)	(0.275,0.366,0.497)	(0.267,0.352,0.470)
C_9	(0.150,0.266,0.426)	(0.240,0.316,0.419)	(0.236,0.315,0.416)	(0.189,0.283,0.408)	(0.192,0.289,0.419)	(0.186,0.278,0.397)
Urban Sustainability and Livability Aspect (MC4)						
C_{10}	(0.277,0.343,0.415)	(0.266,0.334,0.424)	(0.270,0.344,0.441)	(0.263,0.329,0.415)	(0.215,0.298,0.407)	(0.277,0.338,0.408)
C_{11}	(0.263,0.329,0.415)	(0.281,0.348,0.424)	(0.253,0.328,0.424)	(0.277,0.343,0.415)	(0.279,0.359,0.468)	(0.277,0.338,0.408)
C_{12}	(0.263,0.329,0.415)	(0.250,0.318,0.408)	(0.253,0.328,0.424)	(0.263,0.329,0.415)	(0.261,0.342,0.450)	(0.263,0.324,0.408)

The remaining elements of the criterion $\widetilde{w}_{MC1}$ are obtained similarly. That's how we get the final value of the criteria $\widetilde{w}_{MC1} = (0.189, 0.244, 0.316)$.

5.2. The results of the proposed model

Steps 1–2: Four alternatives are assessed by six experts under twelve criteria using the linguistic terms given in Table 2, and the evaluations of the alternatives in terms of linguist terms are reported in Table 7.

Later, the initial matrix is created using Eq. (15) with the help of Tables 2 and 7. The elements of the initial matrix are reported in Table 8.

Step 3: The aggregated score values of alternatives in terms of criteria are calculated using Eq. (16) and Table 8. These values are given in Table 9.

Step 4: The normalized values are computed by Eqs. (17)–(19) with the help of Table 9. These normalized values are given in Table 10.

Table 6
Final fuzzy vectors of weight coefficients.

Crit.	Fuzzy weights	
	Global	Local
MC_1	(0.189,0.244,0.316)	–
C_1	(0.273,0.347,0.442)	(0.052,0.085,0.140)
C_2	(0.24,0.315,0.412)	(0.045,0.077,0.130)
C_3	(0.264,0.338,0.433)	(0.050,0.083,0.137)
MC_2	(0.196,0.251,0.321)	–
C_4	(0.259,0.337,0.436)	(0.051,0.084,0.140)
C_5	(0.233,0.312,0.417)	(0.046,0.078,0.134)
C_6	(0.274,0.351,0.456)	(0.054,0.088,0.144)
MC_3	(0.198,0.252,0.321)	–
C_7	(0.280,0.367,0.488)	(0.055,0.093,0.157)
C_8	(0.254,0.342,0.464)	(0.050,0.086,0.149)
C_9	(0.200,0.291,0.414)	(0.039,0.074,0.131)
MC_4	(0.198,0.253,0.323)	–
C_{10}	(0.262,0.331,0.418)	(0.052,0.084,0.135)
C_{11}	(0.272,0.341,0.426)	(0.054,0.086,0.138)
C_{12}	(0.259,0.328,0.420)	(0.051,0.083,0.133)

Table 7
The assessment of the alternatives.

Crit.	A_1	A_2	A_3	A_4
C_1	VL; VH; E; VL; AL; E	L; H; ML; E; VH; E	ML; AH; ML; L; AL; E	E; ML; ML; ML; L; ML
C_2	ML; ML; ML; L; VL; ML	L; L; L; E; E; L	VL; L; E; ML; AL; ML	VL; E; E; L; VL; E
C_3	VL; H; E; VL; L; E	L; MH; ML; VL; MH; E	ML; MH; VL; VL; VL; L	ML; MH; L; VL; L; ML
C_4	VL; AL; E; E; AL; ML	ML; MH; VL; ML; ML; E	ML; MH; L; E; VL; MH	VL; AL; VL; E; AL; AL
C_5	VH; MH; H; E; E; MH	MH; VH; VH; MH; H; H	H; AH; MH; E; VH; VH	H; AH; VH; MH; AH; VH
C_6	L; VH; ML; ML; MH; ML	E; H; L; ML; E; ML	ML; E; ML; ML; VL; ML	VL; AL; AL; ML; AL; VL
C_7	VL; VL; ML; AL; AL; L	ML; VL; ML; VL; MH; L	E; VL; VL; ML; VL; VL	L; AL; ML; L; VH; AL
C_8	E; H; VH; MH; AH; H	MH; AH; MH; H; MH; H	H; VH; MH; E; AH; H	VH; VH; H; E; H; VH
C_9	VH; MH; MH; E; AH; H	E; H; E; E; E; H	H; E; H; E; VH; MH	H; VH; MH; E; L; H
C_{10}	AH; VL; H; VL; E; VH	VH; VH; AH; VH; MH; H	H; L; H; E; E; E	VH; AH; VH; MH; H; AH
C_{11}	VL; L; VH; VL; VL; L	ML; VL; L; VL; L; L	L; H; ML; L; ML; ML	AL; VL; AL; AL; AL; VL
C_{12}	VH; E; H; MH; ML; MH	ML; H; AH; AH; H; VH	ML; L; H; MH; E; E	AL; H; AH; H; AH; H

Step 5: The weighted normalized values for each alternative in terms of twelve criteria are calculated by Eq. (20) using the weights of criteria (see Table 6) and Table 10, and are presented in Table 11.

Step 6: The positive ideal solution and negative ideal solution are found by Eqs. (21) and (23) using Table 11, as reported in Table 12.

Step 7: The closeness coefficient $(\alpha_i)$of each alternative is calculated by Eq. (24) with the help of Table 12. The overall values of alternatives are presented in Table 13.

Step 8: The alternatives are ranked with respect to their α_i values, and the final ranking $A_2 > A_3 > A_1 > A_4$. A_2 is the most suitable alternative among the four alternatives because it has the largest overall values, while A_4 is the worst alternative.

5.3. Sensitivity analysis and validation

In the next section, the proposed solution's robustness and sensitivity to changes in subjectively defined parameters are checked. Since the values of such parameters depend on the environment's dynamic conditions and the decision maker's perception, it is necessary to consider their influence on the stability of the initial solution. Also, such an analysis provides the possibility of analyzing the impact of such parameters on the final decision and enables the simulation of different scenarios depending on changing environmental conditions. Since there are two subjective parameters (parameter ϕ and υ_{AIP}) in the proposed multi-criteria methodology, the influence of those parameters on the change of the initial solution is shown in the next part.

a. Simulation of the change of parameter ϕ

In the proposed multi-criteria methodology, a condition was set that the value of the parameter ϕ should be $\phi > 0$; that is, the value $\phi = 2$ was adopted to calculate the initial solution. The following section presents an analysis where the change of the parameter ϕ in the interval [1, 50] was simulated. So, a total of 50 scenarios were created. In the first scenario, the parameter ϕ had a value of one, while the value was increased by one in each subsequent scenario. The influence of the parameter ϕ on the change of each alternative is presented in Fig. 2.

Fig. 2(a)–(d) shows the change in closeness coefficients of individual alternatives. The results show that the initiated solution depends on the choice of the value of the parameter ϕ. Fig. 3 compares the changes in the closeness coefficients of the alternatives.

Figs. 2 and 3 show that the closeness coefficients of alternatives A_1, A_2, and A_3 increase proportionally through the 50 scenarios, while the closeness coefficient of alternative A4 decreases. However, these changes occur in a small criterion interval and cause negligible changes in the final values of the alternatives. Therefore, based on the presented results, we can conclude that the initial ranking $A_2 > A_3 > A_1 > A_4$ is confirmed and that the alternative A_2 represents the dominant solution regardless of the parameter ϕ.

b) Simulation of change of absolute anti-ideal point (υ_{AIP})

Absolute anti-ideal point (AIP) is a subjective parameter used to define the reference relations between the logarithmic functions used to calculate the weighting coefficients of the criteria. Eq. (10) defines that

Table 8
The aggregated initial matrix.

Crit.	A_1	A_2	A_3	A_4
C_1	(3.06,3.88,4.71)	(4.35,5.35,6.35)	(3.55,4.38,5.03)	(3,4,5)
C_2	(7,3.5,4.5)	(5.85,3.67,4.67)	(4.05,3.18,4.02)	(2.69,3.68,4.68)
C_3	(5.53,4.03,5.02)	(7.01,4.35,5.34)	(3.87,3.19,4.18)	(2.69,3.68,4.68)
C_4	(2.36,3.03,3.7)	(2.18,4.18,5.17)	(2.73,4.35,5.34)	(1.54,2.04,2.55)
C_5	(2.15,6.17,7.17)	(2.78,7,8)	(3.86,7.17,8)	(6.84,7.84,8.5)
C_6	(7.67,4.85,5.85)	(5.84,4.68,5.67)	(6.17,3.84,4.84)	(1.35,1.86,2.37)
C_7	(3.18,2.18,2.86)	(3.69,3.52,4.51)	(6.69,2.85,3.85)	(2.73,3.4,4.06)
C_8	(2.73,7.01,7.84)	(3.03,6.84,7.67)	(5.2,7.01,7.84)	(6.17,7.17,8.17)
C_9	(6.68,6.84,7.67)	(5.19,5.67,6.67)	(5.02,6.34,7.34)	(5.01,6.01,7.01)
C_{10}	(4.35,5.54,6.36)	(5.35,7.67,8.5)	(7,5.34,6.34)	(6.84,7.84,8.5)
C_{11}	(5.68,3.39,4.37)	(6.01,2.84,3.84)	(7.01,4.18,5.18)	(1,1.34,1.68)
C_{12}	(4.02,6.01,7.01)	(2.68,7.34,8.01)	(7.34,5.01,6.01)	(5.86,6.69,7.19)

Table 9
The aggregated score values.

Alternatives	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
A_1	3.88	4.25	4.44	3.03	5.67	5.49	2.46	6.43	6.95	5.48	3.94	5.84
A_2	5.35	4.20	4.96	4.01	6.46	5.04	3.71	6.34	5.76	7.42	3.53	6.68
A_3	4.35	3.47	3.47	4.24	6.76	4.39	3.66	6.84	6.29	5.79	4.82	5.56
A_4	4.00	3.68	3.68	2.04	7.78	1.86	3.40	7.17	6.01	7.78	1.34	6.64

Table 10
The normalized values.

Alternatives	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
A_1	1.00	0.81	0.78	0.67	0.73	0.34	1.00	0.90	1.00	0.70	0.34	0.88
A_2	0.73	0.82	0.70	0.51	0.83	0.37	0.66	0.88	0.83	0.95	0.38	1.00
A_3	0.89	1.00	1.00	0.48	0.87	0.42	0.67	0.95	0.90	0.74	0.28	0.83
A_4	0.97	0.94	0.94	1.00	1.00	1.00	0.72	1.00	0.86	1.00	1.00	0.99

Table 11
The weighted normalized values.

Alternatives	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
A_1	0.09	0.07	0.07	0.06	0.06	0.03	0.10	0.08	0.08	0.06	0.03	0.08
A_2	0.06	0.07	0.06	0.04	0.07	0.03	0.06	0.08	0.06	0.08	0.03	0.09
A_3	0.08	0.08	0.09	0.04	0.07	0.04	0.07	0.09	0.07	0.06	0.02	0.07
A_4	0.09	0.08	0.08	0.09	0.08	0.09	0.07	0.09	0.07	0.09	0.09	0.09

Table 12
The positive and negative ideal solutions of alternatives.

Criteria	A_1	A_2	A_3	A_4	Criteria	A_1	A_2	A_3	A_4
C_1	0.0006	0.0000	0.0002	0.0005	C_1	0.0000	0.0006	0.0001	0.0000
C_2	0.0000	0.0000	0.0002	0.0001	C_2	0.0002	0.0002	0.0000	0.0000
C_3	0.0000	0.0000	0.0007	0.0004	C_3	0.0004	0.0007	0.0000	0.0000
C_4	0.0003	0.0000	0.0000	0.0021	C_4	0.0008	0.0019	0.0021	0.0000
C_5	0.0005	0.0002	0.0001	0.0000	C_5	0.0000	0.0001	0.0001	0.0005
C_6	0.0000	0.0000	0.0001	0.0037	C_6	0.0037	0.0034	0.0028	0.0000
C_7	0.0011	0.0000	0.0000	0.0000	C_7	0.0000	0.0011	0.0010	0.0007
C_8	0.0001	0.0001	0.0000	0.0000	C_8	0.0000	0.0000	0.0000	0.0001
C_9	0.0000	0.0002	0.0001	0.0001	C_9	0.0002	0.0000	0.0000	0.0000
C_{10}	0.0007	0.0000	0.0005	0.0000	C_{10}	0.0000	0.0005	0.0000	0.0007
C_{11}	0.0000	0.0001	0.0000	0.0042	C_{11}	0.0035	0.0031	0.0042	0.0000
C_{12}	0.0001	0.0000	0.0002	0.0000	C_{12}	0.0000	0.0002	0.0000	0.0002
Distances	0.0582	0.0243	0.0454	0.1053	Distances	0.0936	0.1076	0.1018	0.0473

Table 13
The positive and negative ideal solutions of alternatives.

Alternatives	Δ^+	Δ^-	α_i	Ranking
A_1	0.058	0.094	0.616	3
A_2	0.024	0.108	0.816	1
A_3	0.045	0.102	0.692	2
A_4	0.105	0.047	0.310	4

AIP has a value from the interval $]0,1[$. During the initial solution calculation, we adopted the AIP's value in the middle of the interval $]0,1[$, i.e., the value was adopted $\upsilon_{AIP} = (0.4, 0.5, 0.6)$. Since the relations between the logarithmic functions in the LMAW model are defined based on the AIP value, the question arises of whether other AIP values from the interval $]0,1[$ affect the change of the initial solution.

In the following section, ten scenarios were formed during which the change of AIP was simulated. Also, the influence of other AIP values on the change in the weighting coefficients (see Fig. 4) and on the change of the closeness coefficients of the alternatives (Fig. 5) was analyzed.

In the first scenario, the value $\upsilon_{AIP} = 0.001$ was adopted, while AIP was increased by 10 % in each subsequent scenario. For each AIP change, a new vector of weight coefficients is defined (see Fig. 4). In the next step, the influence of newly formed vectors of weight coefficients on the change of closeness coefficients of alternatives was analyzed (see Fig. 5).

The results from Fig. 4 confirm the dependence between the adopted reference value of AIP and the weight coefficients of the criteria. Also, the results from Fig. 5 show the dependence between the closeness coefficients of the alternatives and the AIP value. From Fig. 5(a)–(d), we can see that the increase in AIP affects the uniform change in the closeness coefficients of all alternatives. However, such changes do not lead to a change in the initial ranks of the alternatives and cannot jeopardize the initial rank. The presented analysis showed that alternative A_2 represents the best solution from the considered set, and has enough potential to be chosen as the optimal solution.

6. Results and discussion

The proposed alternatives do not have the same impact in terms of cost and benefit during the integration of the Metaverse and traffic safety. The alternatives are listed in the following order, from worst to best: used as a hotspot safety driver in the Metaverse, tutor for inexperienced drivers, safety check for sharing economy implementation in traffic, and used for training and managing public transportation vehicles and drivers.

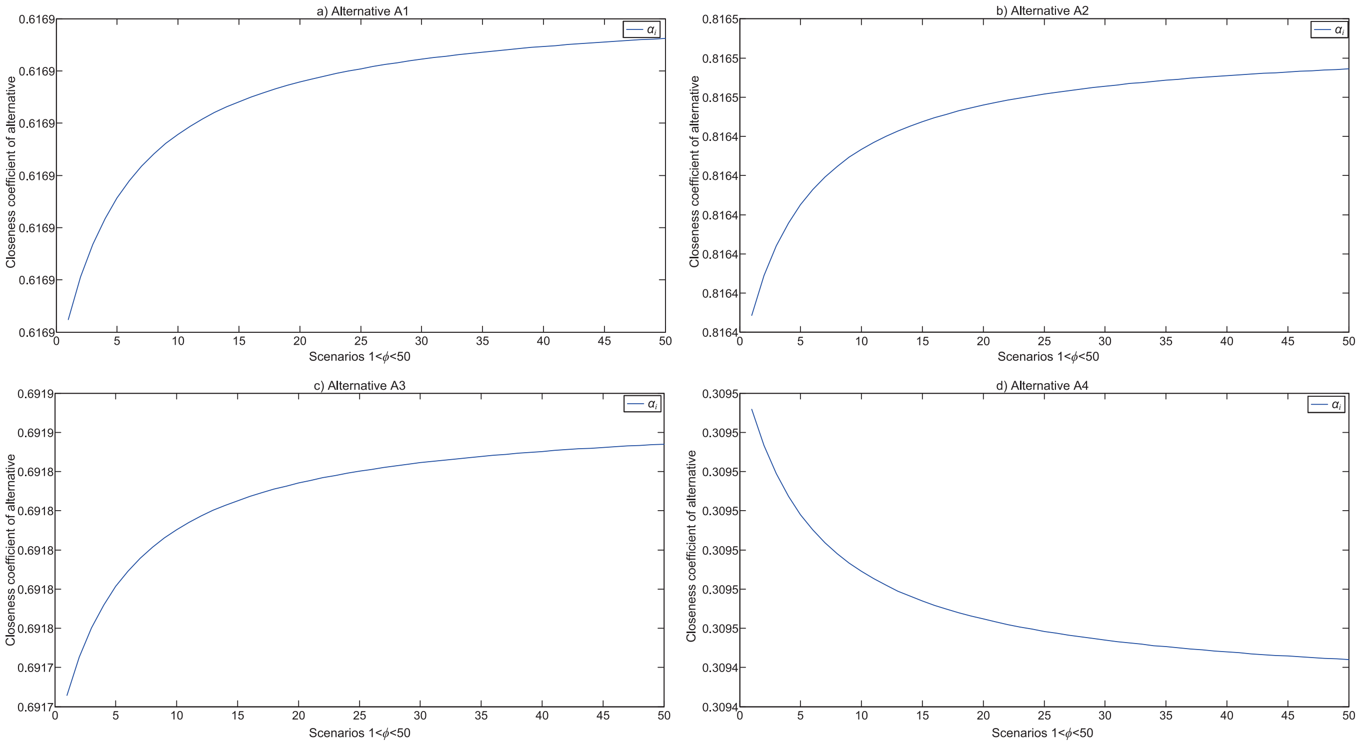

Fig. 2. The influence of the parameter ϕ.

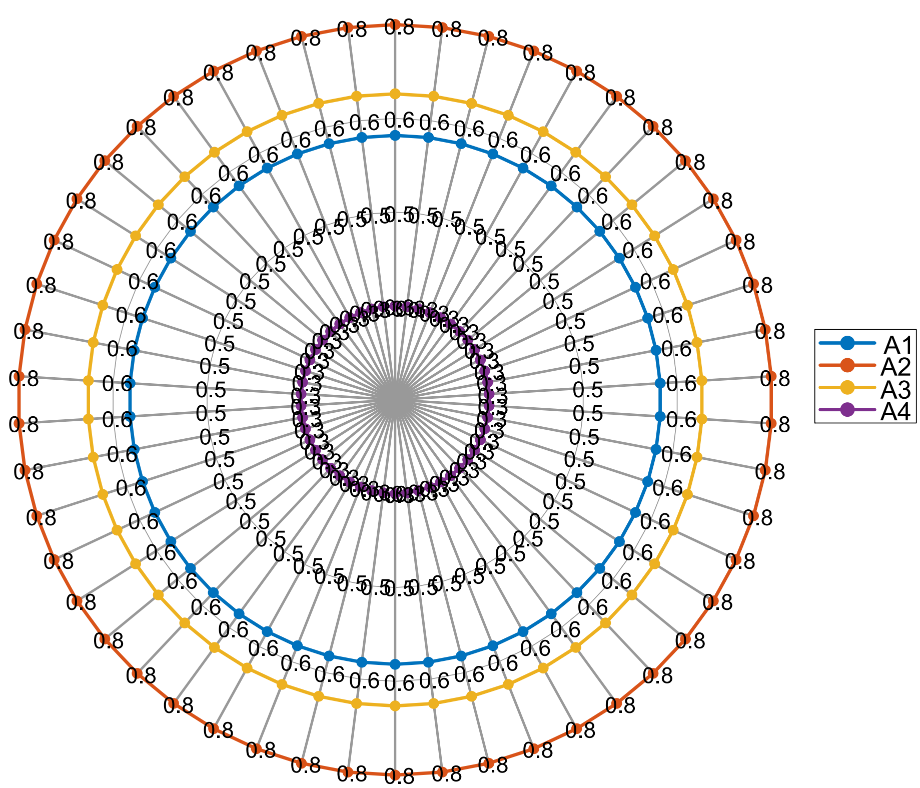

Fig. 3. Comparative presentation of changes in closeness coefficients of alternatives: The influence of the parameter ϕ.

A_4 is the worst in terms of advantage prioritization. There are currently some applications, such as sending messages to drivers as they approach hotspots to avoid accidents. One of the primary reasons it is the worst option is its lack of internet connectivity. The speed of internet connectivity is critical because it allows for effective communication with administrators, quick response to an accident, and quick alert to police and security services. Its deficiency may result in negative outcomes (Fleischer et al., 2012). It can work because it uses comparable methods and will improve in the following stages. Internet connectivity is important during intercity transportation, and as a result, hotspots are becoming more prevalent on intercity roads. Because internet access may not be available on these intercity roads, this alternative is evaluated as the worst.

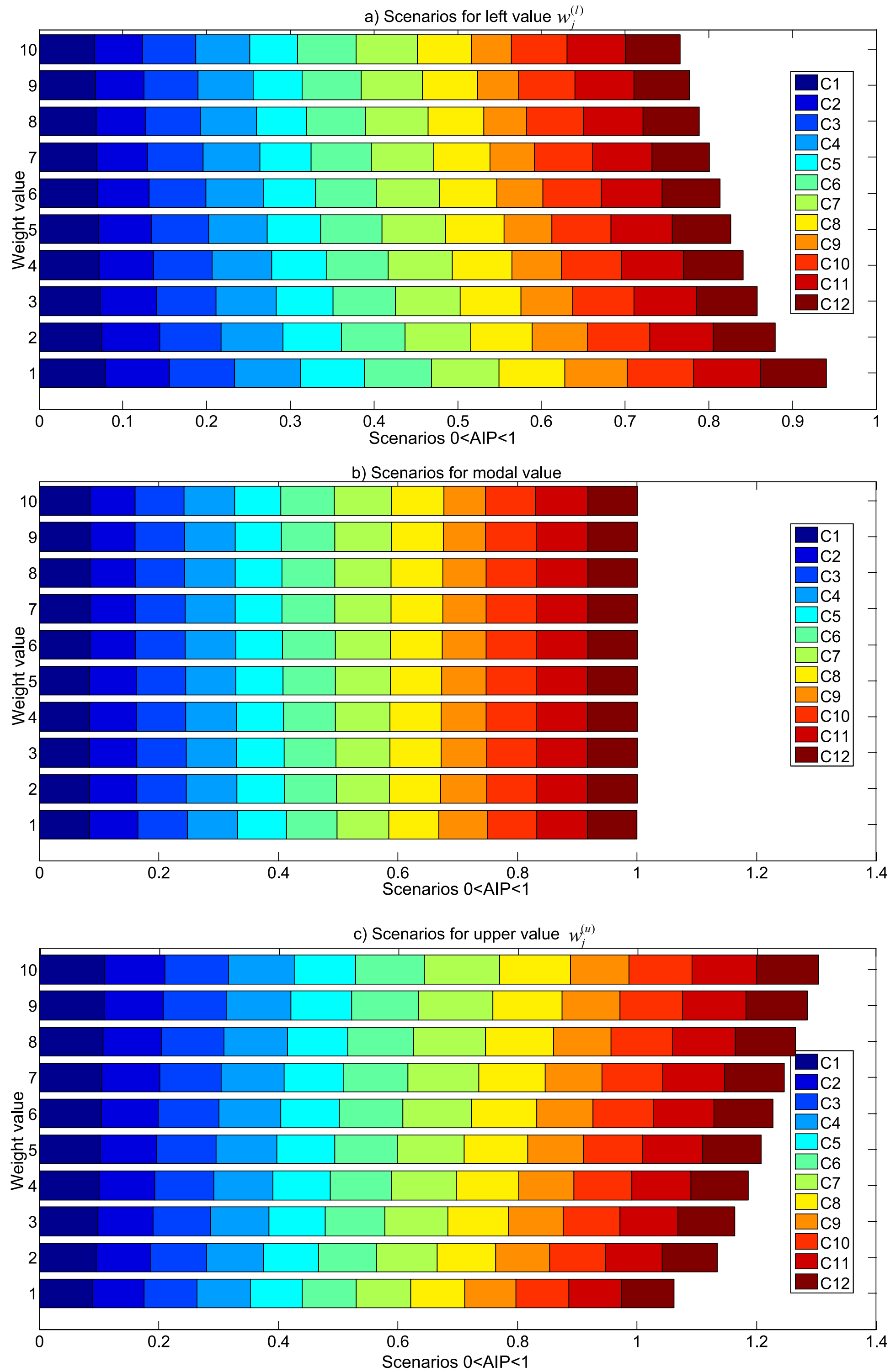

Fig. 4. The influence of AIP on the change of weight coefficients of criteria.

Although A_1 provides benefits to users, it may be listed in this order due to its limited usage area. The Metaverse is a virtual world where users can interact with digital objects and other users in a simulated environment. However, A_1 may be considered a weaker alternative due to its limited usage area. This means that the Metaverse may not be widely available or accessible for all drivers to use for training purposes. Furthermore, decision-makers may view A_1 as unnecessary, since some training is typically provided during the driver's licensing process. Therefore, even if A_1 is effective in teaching new drivers, it may not be selected or implemented due to its limited usage area and the perceived redundancy of providing additional training beyond what is already required for licensing. Although A_1 has potential benefits for teaching new drivers, its limited usage area and redundancy in the licensing process may make it less appealing to decision-makers.

Users usually require assistance to use car-sharing applications. As a result, it is evaluated as the second-best alternative. Especially, elderly people and those who lack technological knowledge may have difficulty using these applications. In the Netherlands, for example, elderly

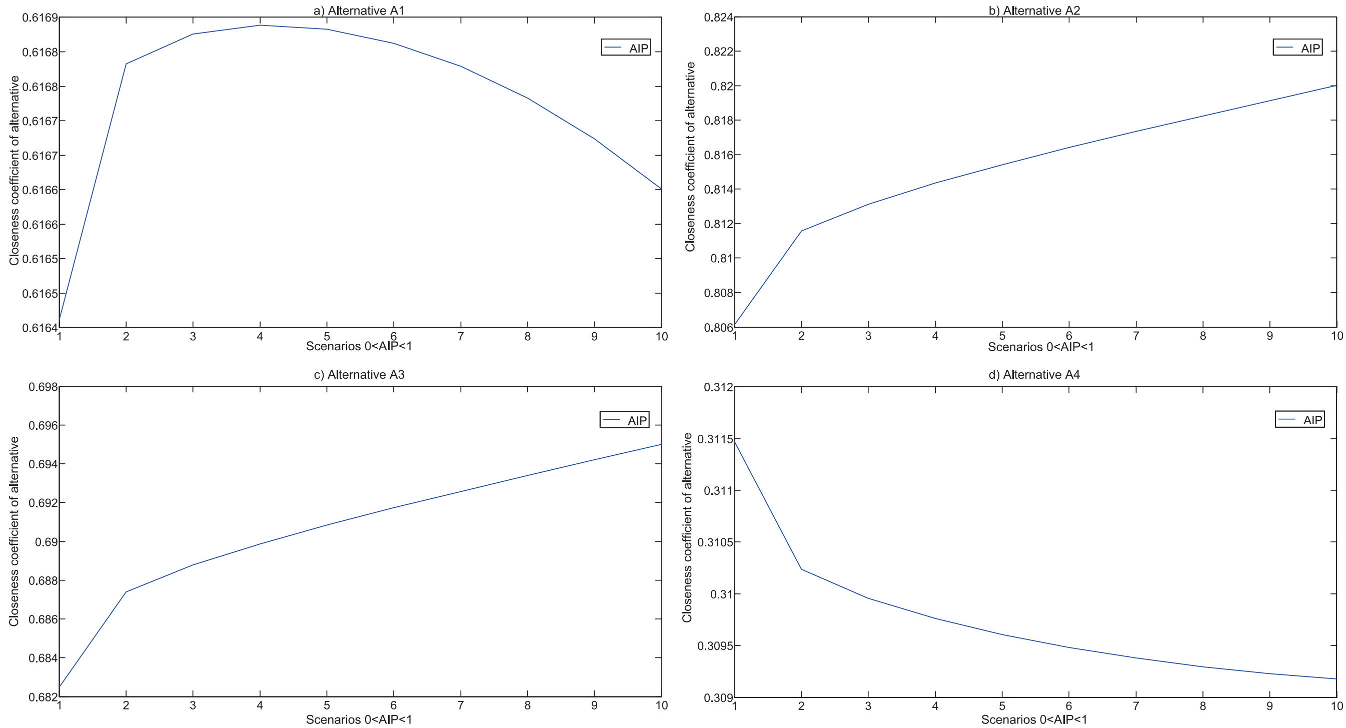

Fig. 5. The influence of AIP on the change of closeness coefficients of alternatives.

respondents are less likely to use electric car-sharing services, and their applications and lower behavioral intention among elderly respondents are also explained by a higher level of anxiety (Curtale et al., 2021). Furthermore, these applications can be extremely useful for controlling and monitoring the tools used in fleet management. As a result, it is evaluated as the second-best alternative. This alternative can be advantageous in preventing these issues.

Finally, A_2, which involves using the Metaverse for training and managing public transportation vehicles and drivers, is considered the best alternative due to its potential impact on reducing accidents and promoting safer driving practices. This is especially important given the high risk of accidents involving public transportation vehicles, which can result from a range of factors, including driver error, technical problems, and inadequate training (Brunoro et al., 2015). By providing training programs and situational training through the Metaverse, this alternative can help to prevent future accidents and create significant advantages for the transportation industry.

7. Implications

As of the year 2022, the speculations about the Metaverse are slowly being replaced by actual information. Its futuristic benefits of it will be required in a variety of fields, including transportation. If this technology is implemented, not only will public transportation become more productive, but it will also be safer. People's perceptions of public transportation as being trustworthy will improve as a result, which will lead to an increase in ridership. As a result, decision-makers need to put a lot of thought into how to best facilitate an increase in ridership and develop cutting-edge solutions in this sector. In addition to that, to support the new plan, it is necessary to utilize micromobility modes for this integration.

The proposed flexible nonlinear function improves the flexibility of the traditional TOPSIS method, and additionally objectifies reasoning when solving real decision-making problems. As an overall result of the study, a decision-making mechanism is presented to the authorities. Although alternatives and criteria may change according to the demands of the municipality and the perception of the population, the methods used in this study can be applied regardless of the number and type of alternatives and criteria. Therefore, this study contributes to the literature as it is a flexible method that all authorities can use when deciding to go through a decision-making process. For future studies, our study provides a basis on which other studies can be built on different topics, different alternatives, and different criteria.

8. Conclusion

This study concluded that public transportation is the most appropriate area for Metaverse on traffic safety due to its widespread use. This integration is thought to be necessary for urban transportation and safety. Despite its positive impact, the incorporation of this new technology into traffic systems has some safety limitations. First and foremost, we created four alternatives based on the case study city's opportunities; however, the potential of these alternatives may differ in different cities. These variants should be adjusted. Second, depending on the city's capabilities, the criteria may change. They can be increased or decreased, which is why they can be altered by conducting a larger study. These technologies' application areas will expand as they become more widely used in the future. As a result, decision-makers must evaluate these criteria and objectives concurrently, and new alternatives determined by needs in future studies should be addressed in new studies. As a result, this study provides decision-makers with insight into how the Metaverse can improve traffic safety.

This study has some limitations. Calculations can be complex due to the complexity of the mathematical model of the proposed method. A software tool can be developed for this. It can also be difficult to find Metaverse experts to fill out the questionnaire. For this, an online questionnaire can be prepared, and it can be sent to relevant academicians or companies. Another limitation is that an expert cannot evaluate all criteria with the same expertise. In future studies, the proposed method can be integrated with various fuzzy sets. At the same time, the proposed method can be hybridized with the multi-criteria decision-making methods in the literature.

CRediT authorship contribution statement

Muhammet Deveci: Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Dragan Pamucar:** Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Ilgin Gokasar:** Conceptualization, Data curation, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Mario Köppen:** Supervision, Validation, Writing – review & editing. **Brij B. Gupta:** Supervision, Writing – review & editing. **Tugrul Daim:** Supervision, Validation, Writing – original draft, Writing – review & editing.

Data availability

The data that has been used is confidential.

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