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Sustainable Urban Transportation: Key Criteria for a Greener Future

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ABSTRACT

A sustainable transportation network has become increasingly critical for society as urban growth, environmental challenges, and transport system inefficiencies intensify. The seamless application of multi-criteria decision analysis (MCDA) as an analytical framework enables the identification, weighting, and ranking of key sustainability criteria across economic indicators, environmental factors, and social sustainability measures. The Fuzzy Logarithm Methodology of Additive Weights (F-LMAW) serves as an analytical tool to evaluate, weigh, and rank these criteria under uncertain conditions. In this study, F-LMAW—incorporating Triangular Fuzzy Numbers (TFNs)—is applied to assess sustainable transport criteria across different sustainability dimensions. The analysis integrates expert surveys, current literature, and findings from completed transportation projects to introduce five new sustainability criteria. The results reveal that safety, health, and greenhouse gas emissions are the most critical sustainability factors. Furthermore, transportation system design should prioritize human well-being and environmental protection. While economic factors, particularly infrastructure costs, remain essential, they must be evaluated alongside long-term operational sustainability requirements. This research provides a structured approach to help authorities systematize transportation funding decisions, optimize resource allocation, and integrate sustainable practices into urban transport systems.

1. Introduction

Worldwide urban development has increased the demand for sustainable transport systems due to issues arising from inadequate infrastructure, air and noise pollution, traffic congestion, and related challenges [1]. The impacts on climate change are substantial due to this [2,3]. To be classified as sustainable, transportation systems must fulfill three requirements, that are accessibility, affordability, and reducing waste while limiting the use of non-renewable energy sources [4]. An efficient, sustainable transport design enhances quality of life for society [5]. Sustainable development and city resilience require public engagement throughout the urban transportation planning process. Citizen participation in transportation policy development ensures that local community needs and preferences receive proper consideration [6]. The inclusive development methods produce effective transportation solutions that balance fairness, sustainability, and operational performance [7,8]. Integrating citizens into decision-making allows cities to identify transportation priorities and address the underlying problems affecting travel. Policymakers gain

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valuable knowledge to develop infrastructure and service solutions that enhance accessibility, lower congestion, and minimize environmental impact [9].

Sustainable transportation provides a strong foundation for economies to achieve sustainable development goals [10]. The transport sector accounts for approximately 25% of global emissions, driven largely by the growing consumption of fossil fuels. Energy demand from the sector continues to grow, with a 4% rise in 2022 compared to pre-pandemic levels. This growth can be attributed to the consumption of fossil fuels [11]. The issue highlights the importance of transport technologies powered by renewable and clean energy [12]. The transportation industry in low- and middle-income economies is expected to contribute to the rising carbon emissions, posing a challenge to the successful implementation of the 2030 Agenda for sustainable development [13]. Without urgent sustainability efforts, transportation can lead to an approximated US$70 trillion in economic losses by 2050, escalating resource usage and environmental degradation [14]. As the world becomes more interconnected, sustainable transportation systems are essential for generating economic value while protecting environmental health. The European Conference of Ministers of Transportation introduced development goals to establish transportation systems that integrate social, economic, and environmental sustainability [15].

From an economic standpoint, the transport sector and market operations are essential for economic growth. Successfully balancing contradictory transportation priorities requires government officials to invest in multi-modal systems, support clean technology adoption, and strongly control emissions while maintaining accessibility for all citizens at affordable rates. A worldwide strategic initiative becomes vital to creating sustainable transport solutions because future urban mobility must embrace economic and environmental needs together [16]. Enhancing transportation quality through speed improvement, market connectivity, and accessible networks leads to substantial savings for all users in both their personal lives and business operations [17,18]. Ecologically, the transportation sector significantly impacts the environment by releasing carbon dioxide, physical footprints, and interactions with nature, all of which contribute to air pollution [19,20]. The technological development of alternative fuels like hydrogen-powered vehicles and electric mass transportation with autonomous operations offers an encouraging avenue toward reducing the sector's carbon footprint without compromising operating efficiency. The transport sector contributes elevated levels of pollution, which seem to increase each year. In 2018, the emissions reached a record high of 29% [21]. Through the European Green Deal, the initiative aims to achieve a 90% emissions reduction by 2050. The deal also entails purposes beyond pollution control [22]. People worldwide mostly experience excessive transportation noise from road traffic, though noise pollution also originate from railways, aviation, and industries. Transport-related pollution from public and private vehicles proves to be the main air contaminant in metropolitan areas, posing health risks to residents [23,24].

Sustainable transportation planning requires decision-makers to analyze multiple criteria that frequently compete against one another across economic, environmental, and social pillars. These complexities require MCDA methods and their structured frameworks for alternative assessment using multiple factors, as traditional approaches fail to address the complexities effectively. In this study, fuzzy logic is implemented as a method to strengthen decision-making processes in uncertain situations by managing specialized and imprecise analysis methods.

The field of MCDA features a multitude of approaches used to establish criterion weights and rank alternatives through Analytic Hierarchy Process (AHP) [25], Step-wise Weight Assessment Ratio Analysis (SWARA) [26], Best-Worst Method (BWM) [27], 2015), and Logarithm Methodology of Additive Weights (LMAW) [28]. LMAW distinguishes itself from other methods since it operates efficiently and generates dependable results while maintaining stability when used for dynamic decision-making. Other decision methods are more susceptible to rank reversal, whereas LMAW maintains reliable results despite changes to decision elements.

Although LMAW proves effective, traditional MCDA lacks the capability to handle complete expert opinion uncertainty. This study modifies LMAW by using Triangular Fuzzy Numbers (TFNs) from fuzzy logic to build an advanced weight determination process that delivers better adaptability and reliability. Sustainability evaluations during transportation planning become more accurate because fuzzy number integration allows the conversion of subjective information into quantifiable data. The paper contains five significant contributions, as follows:

i. Development of a Fuzzy-Based MCDA Framework for Sustainable Transportation: The study presents a structured method based on the F-LMAW, which enables sustainable criterion assessment and ranking in transportation decision-making by resolving expert judgment uncertainty,
ii. Comprehensive assessment of sustainability criteria: It combines all three sustainable transportation pillars into one framework for delivering detailed sustainable priority assessments,
iii. Objective criteria weighting and ranking: Utilizing fuzzy numbers in the study improves weight determination precision through unbiased methods, which yields superior assessment reliability and transparency for sustainability reviews,
iv. Practical insights for policymakers and urban planners: The research findings offer quantitative information that enables transportation authorities to select optimal investment areas, achieve maximum practical resource allocation, and develop infrastructure that supports sustainability targets, and
v. Demonstrates how to connect theoretical frameworks to actual field applications: The study delivers two key benefits to the academic community: it advances fuzzy MCDA applications in transportation as well as providing a specific tool for actual use in urban mobility planning.

The rest of the paper is structured as follows: Section 2 includes a literature review of sustainable transportation coupled with MCDA application. The literature review also highlights the existing research gaps. Section 3 explains the problem statement, and section 4 details the methodology of F-LMAW and the criteria weighting and ranking approach. Section 5 demonstrates the application of the method, and section 6 entails the analysis of sustainability criteria and as well as results relating to weight coefficients and rankings. Section 7 includes a critical discussion, analysis of key findings and policy implications. The paper is concluded in Section 8, highlighting the future research pathways.

2. Literature Review

The transport sector, widely recognized as one of the fundamental sectors of the economy, has a critical role in driving economic development by creating essential linkages between production, exchange, and consumption activities necessary for a thriving marketplace. As transport services are upgraded and optimized, they significantly stimulate economic growth while simultaneously enhancing the overall standard of living and quality for society [29]. It is, however, necessary to recognize that transport also has immense and far-reaching negative impacts on society and the environment. Such negative impacts entail a huge consumption of resources, vast pollution, and environmental degradation attributed to transport vehicles and the transport infrastructure [30]. One of the most pressing concerns in recent years relates to the emission of various air pollutants, including carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC). These substances pose serious health risks to human beings, which can lead to a variety of health problems, and also have huge social costs, which can overwhelm societies and healthcare systems [31].

Traditional transportation systems now present growing challenges, stressing the need to develop efficient and responsible mobility solutions. Although transportation has long been as a catalyst for economic and social progress, its current trajectory is unsustainable. Moreover, climate change, and the rising global energy demand, have made transportation sustainability a key and pressing issue [32]. According to the International Energy Agency, the total energy demand is set to see a dramatic rise of 30% by 2040. The combination of fast-rising populations and urban growth within major cities has created greater energy demand and fossil fuel dependence, which subsequently result in environmental challenges such as atmospheric pollution. Fossil fuels represent a major portion of transportation fuel consumption, which makes engines a primary contributor to air pollution and climate change [33]. The scientific community operates under a directive to prohibit fossil fuel-based vehicles alongside the promotion of environmental-friendly transportation systems [34]. A solution must integrate economic progress and environmental protection with social equity in order to affectively address these problems. The development leads to sustainable transportation, which tackles environmental hazards through accessible and affordable services that preserve operational efficiency.

2.1. Sustainable transportation

The term “sustainable transportation” was originally coined by Replogle [35] at the Transportation Research Board Annual Meeting, a seminal event in the field of “sustainable transportation strategies” [36]. Since that seminal event, researchers have endeavored to frame the concept of sustainable transportation in three principal and underlying dimensions: economic development, which considers the fiscal sustainability and growth of communities; environmental conservation, which emphasizes protecting our natural environment; and social welfare, which highlights the imperatives of equitable access to transportation for all [37]. In the last several years, measuring and examining the efficiency of transportation sustainability has been a prevailing theme in this academic field, as it offers valuable information on how transportation systems can be effectively optimized and improved toward the ends of long-term sustainability and resilience [38]. The holistic concept of sustainable transport aims to unite human transportation requirements with basic sustainability attributes related to environmental preservation, social welfare, and financial stability. Compared to traditional transportation planning, sustainable transport adopts an expanded approach by integrating environmental protection, resource conservation, and its traditional efficiency-driven orientation. The main objective of sustainable transport is thus to launch and construct transportation systems that provide both ecological footprint reduction and affordable, accessible, and efficient solutions for the present and future generation.

Researchers have established multiple evaluation tools that help improve sustainable transportation systems. Castillo and Pitfield [39] designed a framework that aids decision-makers in transportation planning in identifying suitable sustainability indicators. Jeon et al., [40] recognized transportation mobility as vital, alongside system performance, in building sustainable transportation systems. the authors also introduced system effectiveness to evaluate transport sustainability. The transport sustainability measurement for Melbourne, Australia, presented by Reisi et al., [41], combines nine indicators that address social, environmental, and economic factors. The Taiwanese transport sustainability measurement undertaken by Shiau et al., [42] utilized 19 key economic, environmental, societal, and energy-based indicators. Persia et al., [43] presented a method to evaluate the transport sustainability of 50 Italian cities using state indicators together with sustainability indicators and policy indicators. Sayyadi and Awasthi [44] conducted a study to determine the complexity of the transportation system while assessing sustainability strategies by evaluating congestion measures alongside fuel usage and greenhouse gas creation. De Almeida Guimarães and Junior [45] conducted a study that examined environmental sustainability strategies to develop and upgrade transportation systems while moving towards sustainable development. The study by Schemme et al., [46] presented sustainable non-fossil alternative diesel fuels originating from renewable energy sources. De Souza et al., [47] examined electric and battery-powered vehicles and their impact on reducing greenhouse gas emissions to enhance environmental sustainability. Godil et al., [48] analyzed how renewable energy serves the transportation sector by reducing economic costs and CO2 emissions. The study demonstrates how renewable energy integration in transportation systems creates new technologies and reduces atmospheric greenhouse gases. Pathak et al., [49] introduced an extensive approach to identify sustainable transport evaluation measures. The authors also posit that system performance evaluation results in better sustainability outcomes. Shokoohyar et al., [50] studied the correlation between road safety and fuel consumption when analyzing transportation infrastructure quality and stressed the need for implementing sustainability protocols.

Existing studies have also focused on developing alternative fuel sources and ecological vehicle technologies. Wang et al., [51] conducted assessments of road transportation systems to determine which ones could effectively be developed within the Organization for Economic Cooperation and Development. Azamian [12] presents a sustainable development model for climatic zones that should be implemented. Simultaneously, the study demonstrates a sustainable transportation system powered by zero-emission vehicles, supported by renewable energy supply technologies, in addressing the problem. Recent developments studied by Abdelati [52] focus on high-speed railway projects, metro system enlargements, and environmentally sustainable transport initiatives affecting the transport network; In the study, official reports, case studies, and scholarly literature are used to evaluate transportation opportunities and their associated challenges in Egypt. The results of the reviewed research on sustainable transportation are provided in Table 1.

Table 1
Overview of Studies on Sustainable Transportation Evaluation

Researchers	Description of the study
Castillo and Pitfield [39]	Developed a framework to help decision-makers identify suitable sustainability indicators in transportation planning.
Jeon et al. [40]	Recognized transportation mobility and system performance as key factors for sustainability, adding system effectiveness as an evaluation criterion.
Reisi et al. [41]	Measured transport sustainability in Melbourne, Australia, using nine social, environmental, and economic indicators.
Shiau et al. [42]	Assessed transport sustainability in Taiwan using 19 key indicators related to economic, environmental, societal, and energy factors
Persia et al. [43]	Evaluated the transport sustainability of 50 Italian cities using state indicators, sustainability indicators, and policy indicators.
Sayyadi and Awasthi [44]	Analyzed transportation system complexity and assessed sustainability strategies based on congestion, fuel usage, and greenhouse gas emissions.
de Almeida Guimarães and Junior [45]	Examined environmental sustainability strategies for developing and improving transportation systems toward sustainable development.
Schemme et al. [46]	The research focused on discovering renewable energy-based sustainable alternative fuels for diesel use.

Table 1
Continued

Researchers	Description of the study
De Souza et al. [47]	The research assessed how electric and battery-powered vehicles lower greenhouse gas emissions, with the goal of improving environmental sustainability.
Godil et al. [48]	The paper explored how renewable energy power transportation through decreased operational expenses and reduced carbon dioxide emissions and enhanced new technology development.
Pathak et al. [49]	They proposed an extensive approach for evaluation of sustainable transport measures to better understand system performance outcomes for sustainable development.
Shokoohyar et al. [50]	The relationship between road security and fuel usage was assessed to highlight essentials of sustainable transportation protocol design in infrastructure.
Wang et al. [51]	Assessed road transportation systems to determine their development potential within the OECD.
Azamian [12]	Proposed a sustainable development model for climatic zones, advocating for zero-emission vehicles and renewable energy-based transportation systems.
Abdelati [52]	Analyzed contemporary transportation projects, including high-speed rail and metro expansions, using reports, case studies, and scholarly literature to assess Egypt's transport network challenges and opportunities.

2.2. Sustainable Transportation Using the MCDA Approach

Sustainable transportation planning is highly complex as it encompassess three interconnected dimensions: economic aspects, environmental factors, and social considerations. Decision-makers in this sector need to navigate conflicting criteria, asbasic optimization methods that focus on a single objective are ineffective [53]. When dealing with complex transportation problems, the MCDA method provides a superior solution. Multiple MCDA approaches have been developed to evaluate transportation options by integrating various assessment standards. The selection process for solutions that meet sustainability targets depends on decision-making strategies that help stakeholders assess trade-offs. MCDA is extensively applied in transportation research, for example, evaluating fuel efficiency, environmental impact, and infrastructure development. MCDA delivers valuable applications for sustainable transportation policy assessments, selecting preferred transportation projects, and the sequential ranking of transport systems according to their key performance indicators. Existing studies have evaluated several MCDA techniques for transportation sustainability assessments. López and Monzón [54] developed a multi-criteria assessment model through strategic transportation planning that received an integration of sustainability principles. A combination of AHP with Data Envelopment Analysis (DEA), developed by Yang [55], offers an evaluation framework to determine environmental sustainability levels in urban transportation systems. Shiau and Jhang [56] developed a method that combined the Charnes, Cooper, and Rhodes (CCR) model with rough set theory (RST) to measure transportation sustainability in Taiwanese transportation sector. Lin et al., [57] and Wu et al., [58] implemented the CCR model for transportation energy efficiency evaluation. Yang et al., [59] integrated the DEMATEL-ANP model to evaluate sustainable public transport infrastructure projects. Pathak et al., [49] established a performance evaluation method for sustainable freight transportation research by combining the fuzzy AHP, Total Interpretive Structural Modeling (TISM), and a Delphi study. The AHP was adopted for evaluating sustainable public road transportation systems in Madrid by analyzing economic and environmental criteria [60]. Sayyadi and Awasthi [61] used ANP methodology to evaluate transportation policies, considering the levels of congestion, fuel consumption, and greenhouse gas emissions. Ulutaş et al. [62] developed a hybrid MCDM model that integrates the PIvot Pairwise. RElative Criteria Importance Assessment (PIPRECIA) and Combined Compromise Solution (CoCoSo) approaches to rank transportation companies according to their cost-effectiveness and sustainability performance. The study by Devi et al., [63] entails an uncertain assessment of sustainable transport strategies through Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) methodology. Jafarzadeh Ghoushchi et al. [2] introduced a strong hybrid framework development to assess and rank road smartification measures with sustainability targets as a priority. They employed the SWARA and TOPSIS approach based on the Spherical Fuzzy set to evaluate and rank smartening measures for their research. Jafarzadeh Ghoushchi et al., [64] explore how young drivers affect road transportation safety by analyzing the dangers related to drivers under 25, which stem from their inexperience as well as their age-specific characteristics, utilizing the MARCOS method. The results of the reviewed research about transportation and MCDA appear in Table 2.

Table 2
MCDM Methods in Sustainable Transportation Research

Researchers	MCDA Method Used	Description of the Study
López and Monzón [54]	Multi-Criteria Assessment Model	Developed a multi-criteria assessment model integrating sustainability principles into strategic transportation planning.
Yang [55]	AHP + DEA	Proposed an evaluation framework for assessing environmental sustainability in urban transportation systems.
Shiau and Jhang [56]	CCR +RST	Measured transportation sustainability in Taiwan using a combination of two models.
Lin et al. [57]	CCR	Evaluated transportation energy efficiency.
Wu et al. [58]	CCR	Assessed transportation energy efficiency.
Yang et al. [59]	DEMATEL+ANP Model	Evaluated sustainable public transport infrastructure projects.
Sayyadi and Awasthi [61]	ANP	Evaluated transportation policies by analyzing congestion, fuel consumption, and greenhouse gas emissions.
Pathak et al. [49]	Fuzzy AHP +TISM + Delphi	Developed a performance evaluation method for sustainable freight transportation.
Rivero et al. [60]	AHP	Assessed sustainable public road transportation systems in Madrid.
Ulutaş et al. [62]	PIPRECIA + CoCoSo	Developed a hybrid MCDA model to rank transportation companies based on cost-effectiveness and sustainability.
Devi et al. [63]	TOPSIS	Conducted an uncertain assessment of sustainable transport strategies.
Jafarzadeh Ghoushchi et al. [64]	MARCOS	explores how young drivers affect road transportation safety by utilizing the MARCOS method
Jafarzadeh Ghoushchi et al. [65]	SWARA +TOPSIS +Spherical Fuzzy	Proposed strong hybrid framework development to assess and rank road smartification measures with sustainability targets

2.3. Research gap

Existing research about sustainable transportation evaluation does not include a standardized framework for systemically evaluating sustainability criteria in decision-making. Multiple earlier studies determined criteria weights and ranked transportation alternatives by employing the traditional MCDA methods, including AHP, SWARA, and BWM, yet other studies implemented TOPSIS, Multi-criteria Optimization and Compromise Solution (VIKOR), and Multi-Attribute Border Approximation Area Comparison (MABAC) ranking techniques. The applied assessment techniques enable valuable conclusions, yet they struggle to execute handling processes related to uncertainty, the influence of expert judgments, and rank stability. The main obstacle in sustainable transportation decision-making is the natural uncertainty within expert assessment processes. Current MCDA systems have strict requirements for numeric data as input while frequently failing to properly represent precise expert linguistic assessments. Researchers have developed decision models by incorporating fuzzy logic as a solution. The application of fuzzy AHP and fuzzy TOPSIS brings several computational difficulties and rank sensitivity issues to decision-making processes. A new, improved fuzzy-based methodology is presented within this research to unite the F-LMAW. LMAW provides researchers with improved computational performance and sustainably ranks alternatives while remaining adaptable to big data systems. The implementation of TFNs as part of this study enables accurate determination and adaptable weight calculations in sustainable transportation evaluation. The weight assignments in LMAW maintain consistency, which leads to reduced sensitivity toward alternative numbers because this method does not share TOPSIS instability issues. This research unifies traditional MCDA methods with fuzzy decision-making to establish an enhanced stable mathematical framework that performs sustainability assessments in transportation planning.

3. Problem statement

Urban development alongside economic expansion heavily depends on transportation systems as one of the main sources that generate environmental degradation while creating social issues. The combination of fast urban transformations and rising population movement has worsened problems linked to heavy traffic congestion, and this has led to further greenhouse gas emissions, air and noise pollution, and mounting infrastructure expenses. Successful sustainable transportation must combine activities that protect the economy with environmental stewardship and social prosperity. The evaluation process of transportation sustainability demands a complete set of criteria to express its three fundamental dimensions. Economic criteria encompass infrastructure and project development costs, operational and maintenance expenses, and accident-related costs. Resource utilization and ecological impacts join energy consumption, emissions, and pollution to form environmental criteria. Social factors analyze how transportation affects public wellness, safety standards, and community quality and how systems modify business operations and social setups. Decision-makers face difficulties in establishing systematic evaluation of transportation options for sustainability criteria. There is no standardized assessment framework for sustainable transportation, thus impeding relevant authorities from creating strategies and building infrastructure. Decision-makers need a structured decision-making system with clear standards to select alternatives that fulfill economic needs and environmental requirements as well as community demands.

3.1. Critical Criteria

This section concisely describes each sub-criterion, with the criteria and sub-criteria outlined in Table 3.

Table 3
Sustainable urban transportation evaluation criteria

Main Criteria	Sub Criteria	Type (Cost/Benefit)
Economic (C_1)	Cost of infrastructure/project development (C_{11})	C*
	Operating cost (C_{12})	C
	Time cost (C_{13})	C
	Maintenance cost (C_{14})	C
	Accident cost (C_{15})	C
Environmental (C_2)	Energy consumption (C_{21})	C
	Resource use (C_{22})	C
	Renewable fraction (C_{23})	B**
	Greenhouse gas emissions (C_{24})	C
	Air pollution (C_{25})	C
	Noise pollution (C_{26})	C
	Effects on species (C_{27})	C
	Landscape degradation (C_{28})	C
	Negative visual impact (C_{29})	C
Social (C_3)	Safety (C_{31})	B
	Health (C_{32})	B
	Quality of life (C_{33})	B
	Impact on business services (C_{34})	B
	Impact on community services (C_{35})	B

*denotes costs, and ** refers to benefit drivers.

Cost of Infrastructure/Project Development (C_{11}): All expenditures related to transportation infrastructure planning, together with architectural design work and construction, form the total project expenses, including material costs, labor payments, and bureaucracy costs.

Operating cost (C_{12}): A transportation system needs recurring expenses to operate through its daily activities, which involve fuel and energy usage, labor payment, administrative fees, and vehicle value depreciation. Continuous transportation service efficiency depends on costs, which enable operational functionality.

Time Cost (C_{13}): The cost to the economy stems from travel delays, including expenditures on transportation system inefficiencies. Travel time, waiting duration, and congestion movement impact create financial losses, which are included in the transportation costs.

Maintenance Cost (C_{14}): Transportation maintenance includes ongoing expenses needed to ensure the proper function and safety of transportation infrastructure. A public national land transportation budget supports evaluations for facility servicing alongside essential maintenance, upgrades, and necessary repairs of roads and bridges.

Accident Cost (C_{15}): Financial expenses from traffic accidents include medical bills, vehicle repairs, legal expenses, and productivity losses due to injuries or fatalities.

Energy Consumption (C_{21}): All energy consumed in transportation operations requires counting vehicle fuel use alongside public transport electric consumption. Higher amounts of energy used create rising operational expenses and negative environmental effects.

Resource Use (C_{22}): Sustainable transportation choices must account for their effects on natural resources. Using resources efficiently, whether in the materials for building infrastructure or manufacturing vehicles, is crucial to reducing environmental damage and preserving limited supplies.

Renewable Fraction (C_{23}): Within the transportation system, the utilization of renewable resources like wind power, solar power, and biofuels determines the energy fraction. Higher renewable power generation reduces fossil fuel needs while reducing environmental damage.

Greenhouse Gas Emissions (C_{24}): Enhanced greenhouse gas emissions immediately trigger climate change. Assessing and decreasing carbon dioxide emissions is a primary Environmental requirement for sustainable transportation decision processes, which aim to choose solutions with reduced environmental impact.

Air Pollution (C_{25}): Environmental complaints about air pollution present a major problem. Sustainable transport systems focus on diminishing the release of air quality-harming pollutants to protect both people's health and natural environments.

Noise Pollution (C_{26}): Noise pollution is a vital environmental effect that affects the transport of goods. The core principle of sustainable choices aims to reduce noise emissions, which results in better environmental standards for living near transportation routes and preserves wild habitats

Effects on Species (C_{27}): Industrial noise pollution is an essential environmental result that conduces transport operations. Sustainable choices reduce noise emissions to establish improved environmental quality next to transportation routes while protecting natural habitats.

Landscape Degradation (C_{28}): Transportation infrastructure development disturbs natural environments and urban settings, producing adverse changes in their appearance, environmental destruction, and lower attractiveness.

Negative visual impact (C_{29}): Transportation infrastructure and activities negatively impact environmental visual quality by disrupting landscapes and creating urban clutter through roads, bridges, signs, and vehicle congestion.

Safety (C_{31}): The system's transportation security levels protect all users from harm by reducing the occurrence of accidents, injuries, and deaths for passengers, pedestrians, and cyclists.

Health (C_{32}): Sustainable transportation systems have three major effects on public health: reduced exposure to pollution, reduced stress from congestion, and the health benefits of walking and cycling.

Quality of Life (C_{33}): Quality of life criteria involve different factors directly influencing resident well-being. Implementing noise reduction and reducing visual intrusions helps develop pleasant neighborhoods with improved community living standards for the residents.

Impact on Business Services (C_{34}): Business operations depend on transportation systems for supply chain efficiency, delivery reliability, and market accessibility. A well-operating transport system enables continuous economic development.

Impact on Community Services (C_{35}): Transportation accessibility improves social inclusion levels across communities by providing essential facilities, including education, healthcare, and recreational spaces.

Figure 1 illustrates the key criteria analyzed in this study, categorizing the economic, environmental, and social aspects of sustainable urban transportation.

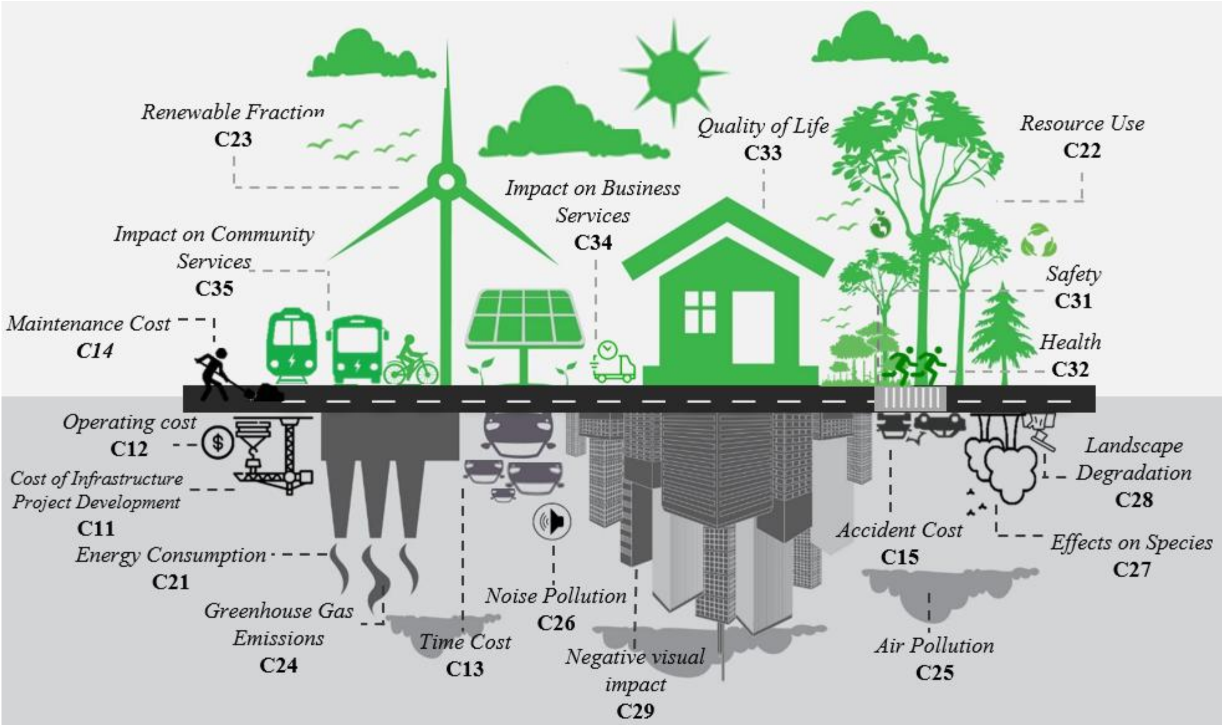

Fig. 1 Sustainable transportation criteria infographic (Author's Design)

4. Methodology

Sustainable transportation planning requires decision-makers to assess various criteria elements that frequently compete between economic sustainability and environmental and social elements. MCDA operates as a structured decision methodology through comprehensive assessment, that integrates factors for decision analysis. Fuzzy numbers increase evaluation reliability, as real-life problems have inherent uncertainties; therefore, the method allows for a flexible approach to criterion assessment. This study uses The LMAW method for weight determination because of its noted stability features, efficient computation capabilities, and clear decision-making objectivity in multi-criteria analysis. The weight determination process with LMAW proves superior to Full Consistency Method (FUCOM), Level-based weight assessment (LBWA), and Ordinal Priority Approach (OPA), since LMAW provides consistent results even when dealing with outlier effects. This research builds on the method by implementing F-LMAW as it aims to enhance robustness within uncertain transportation decision processes. The study employs a ranking system following the weight criterion determination step. This paper elaborates on the MCDA approach by integrating fuzzy numbers and using LMAW methodologies to evaluate criteria and determine ranking results.

4.1. Fuzzy Logarithm Methodology of Additive Weights (F-LMAW)

LMAW enables weight coefficient calculation for criteria and the choice of optimal alternatives from existing sets. This method plays a key role in various application areas to solve challenging decision problems. LMAW has become a trusted MCDM instrument as it delivers dependable weight coefficients. This research utilizes F-LMAW as an extension of LMAW, incorporating TFNs to support decisions making under uncertainty [67]. Fuzzy logic is a powerful decision-making tool as it converts broad data types into numerical forms appropriate for complex real-world scenarios with inherent uncertainty. Fuzzy set theory developed by Zadeh during the 1960s introduced a mathematical model to let elements exist partially within multiple sets suited for expert subjective assessment handling [68]. F-LMAW enhances traditional LMAW by using fuzzy numbers to improve coefficient weight precision. The method offers an objective weighting system for criteria that adapts well to uncertain situations during sustainable transportation decision-making [66]. Figure 2 outlines the steps involved in the fuzzy LMAW approach. F-LMAW establishes a procedure consisting of seven stages explained in the upcoming sections:

Step 1: At the beginning of the F-LMAW approach, the method asks experts $E=\{e_1,e_2,...,e_k\}$ to use a defined fuzzy linguistic scale to evaluate the importance level of criteria $C=\{C_1,C_2,...,C_n\}$. Each criterion gets evaluated by a team of experts (E), who give scores indicating criterion's significance. In other words, the higher the scores, the more important the factor/criterion. Each expert generates priority vectors $\tilde{P}^e=(\tilde{\alpha}^e_{C_1},\tilde{\alpha}^e_{C2},...,\tilde{\alpha}^e_{C_n})$ following the assessment step $e(1\le e\le k)$ through the assignment of the fuzzy linguistic value $\tilde{\alpha}^e_{C_n}$ by the corresponding expert for criterion *n*.

Step 2: Decisions regarding the absolute fuzzy anti-ideal point ($\tilde{\alpha}_{AIP}$) are made by the decision-maker, and it functions as a fuzzy number smaller than the minimum value in the set of priority vectors $\tilde{P}^e=(\tilde{\alpha}^e_{C_1},\tilde{\alpha}^e_{C2},...,\tilde{\alpha}^e_{C_n})$. The reference point enables the evaluation of the relative importance of the criterion throughout the decision-making procedure.

Step 3: The fuzzy relation vector ($\tilde{R}^e$) is derived from an analysis of priority vector $\tilde{P}^e=(\tilde{\alpha}^e_{C_1},\tilde{\alpha}^e_{C2},...,\tilde{\alpha}^e_{C_n})$ components and absolute fuzzy anti-ideal point $\tilde{\alpha}_{AIP}$ values that experts $E=\{e_1,e_2,...,e_k\}$ provide. A specific mathematical Eq. (1) generates this relationship to assess criterion importance during decision-making formally.

$$\tilde{\rho}^e_{C_n}=\left(\frac{\tilde{\alpha}^e_{C_n}}{\tilde{\alpha}_{AIP}}\right)=\left(\frac{\overset{(l)e}{\alpha}_{C_n}}{\overset{(r)}{\alpha}_{AIP}},\frac{\overset{(m)e}{\alpha}_{C_n}}{\overset{(m)}{\alpha}_{AIP}},\frac{\overset{(r)e}{\alpha}_{C_n}}{\overset{(l)}{\alpha}_{AIP}}\right) \tag{1}$$

In this context, l represents the left distribution, and r represents the right distribution of a fuzzy number, while m indicates the value where the membership function (μ) reaches its maximum. Following this, the vector of experts' relations $R^e=(\tilde{\alpha}^e_{C_1},\tilde{\alpha}^e_{C_2},...,\tilde{\alpha}^e_{C_n})$ is derived.

Step 4: The determination of the weight coefficient vector $w^e_j=(\tilde{w}^e_1,\tilde{w}^e_2,...,\tilde{w}^e_n)^T$ for each expert $E=\{e_1,e_2,...,e_k\}$ is achieved by applying the following Eq. (2):

$$\tilde{w}^e_j=\left(\frac{\ln(\tilde{\alpha}^e_{C_n})}{\ln(\prod_{j=1}^{n}\tilde{\alpha}^e_{C_n})}\right)=\left(\frac{\ln(\overset{(l)e}{\alpha}_{C_n})}{\ln(\prod_{j=1}^{n}\alpha^{(r)e}_{C_n})},\frac{\ln(\overset{(m)e}{\alpha}_{C_n})}{\ln(\prod_{j=1}^{n}\alpha^{(m)e}_{C_n})},\frac{\ln(\overset{(r)e}{\alpha}_{C_n})}{\ln(\prod_{j=1}^{n}\alpha^{(l)e}_{C_n})}\right) \tag{2}$$

The left distribution of the fuzzy priority vector is denoted as $\overset{(l)e}{\alpha}_{C_n}$ while $\overset{(r)e}{\alpha}_{C_n}$ represents its right distribution and $\overset{(m)e}{\alpha}_{C_n}$ identifies the value where the membership function reaches one.

Step 5: The weight coefficients $\tilde{w}_j$ combine through Bonferroni aggregator to generate final aggregated fuzzy vectors. The defined methodology enables correct integration of individual weight coefficients from each expert into a unified aggregated vector through Eq. (3).

$$\tilde{w}_j = \left(\frac{1}{k(k-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{k} \tilde{w}_i^{(e)p} \tilde{w}_j^{(e)q} \right)^{\frac{1}{p+q}} = \left\{ \left(\frac{1}{k(k-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{k} w_i^{(l_e)p} w_j^{(l_e)q} \right)^{\frac{1}{p+q}}, \left(\frac{1}{k(k-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{k} w_i^{(m_e)p} w_j^{(m_e)q} \right)^{\frac{1}{p+q}}, \left(\frac{1}{k(k-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{k} w_i^{(r_e)p} w_j^{(r_e)q} \right)^{\frac{1}{p+q}} \right\} \tag{3}$$

The parameters p and $q(\geq 0)$ stabilize Bonferroni aggregators in combination with the weight coefficients $\tilde{w}_j^e$ assigned by expert evaluation $E = \{e_1, e_2, ..., e_k\}$ which are represented by $w_j^{(l_e)}$ for left and $w_j^{(r_e)}$ for right distribution of fuzzy weight when $w_j^{(m_e)}$ indicates the right value where $\tilde{w}_j^e$ reaches its maximum.

Step 6: Determination of the final weight coefficient values $w_j = (w_1, w_2, ..., w_n)^T$ .The weight coefficients of the criteria receive their final value through defuzzification, which involves Eq. (4):

$$w_j = \frac{l + 4m + r}{6} \tag{4}$$

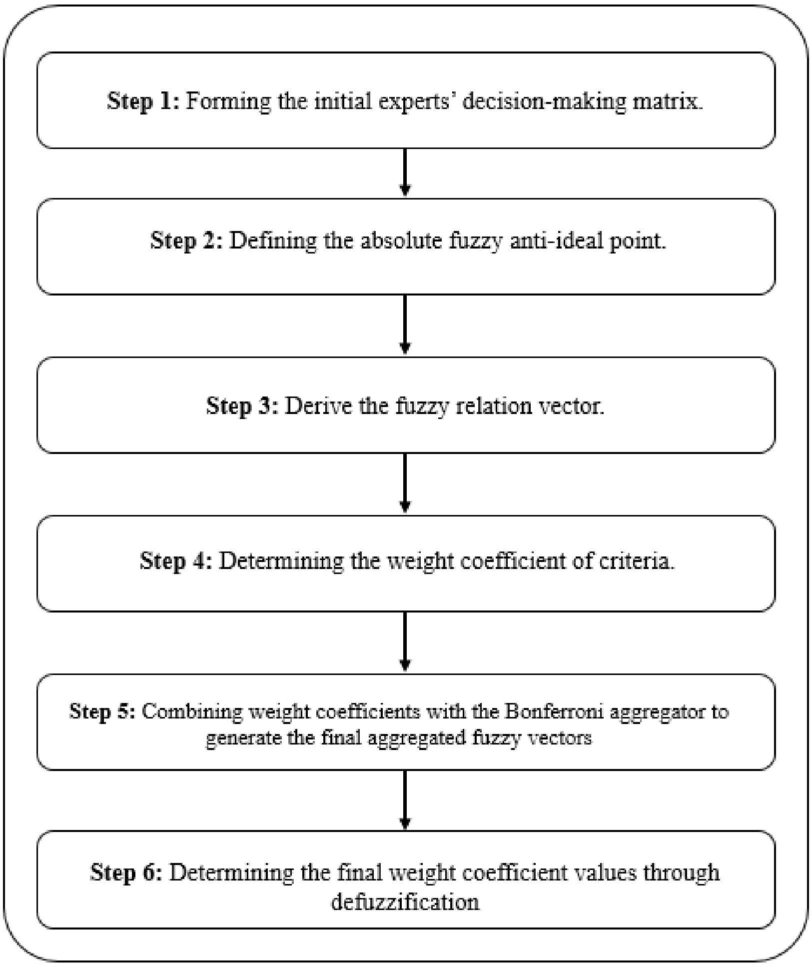

Fig. 2. General overview of the F-LMAW method (Author's Design)

5. Methodology Application

In this section, we apply F-LAMW to assess the importance of criteria for sustainable transportation.

5.1. F-LMAW method application

In this step, the weight coefficients of the criteria are calculated. A panel involving three experts ranks the criteria. A fuzzy linguistic variables scale is employed to facilitate this process, as outlined in Table 4. Table 5. provides the assessment of experts on linguistic variables.

Table 4
Linguistic variables and their abbreviations

Fuzzy Linguistic Descriptor	Abbreviation	Fuzzy Number		
Absolutely Low	AL	1	1	1
Very Low	VL	1	1.5	2
Low	L	1.5	2	2.5
Medium Low	ML	2	2.5	3
Medium	M	2.5	3	3.5
Medium High	MH	3	3.5	4
High	H	3.5	4	4.5
Very High	VH	4	4.5	5
Absolutely High	AH	4.5	5	5

Table 5
Experts' evaluation criteria

Category	Criteria	Cost/Benefit	DM1	DM2	DM3
Economic (C_1)	Cost of infrastructure/Project development (C_{11})	C	VH	H	VH
	Operating cost (C_{12})	C	MH	MH	H
	Time cost (C_{13})	C	M	M	M
	Maintenance cost (C_{14})	C	MH	MH	MH
	Accident cost (C_{15})	C	M	H	H
Environmental (C_2)	Energy consumption (C_{21})	C	VH	VH	MH
	Resource use (C_{22})	C	AH	VH	MH
	Renewable fraction (C_{23})	B	MH	AH	VH
	Greenhouse gas emissions (C_{24})	C	H	AH	VH
	Air pollution (C_{25})	C	MH	VH	H
	Noise pollution (C_{26})	C	M	H	M
	Effects on species (C_{27})	C	AH	VH	MH
	Landscape degradation (C_{28})	C	VH	H	M
	Negative visual impact (C_{29})	C	AL	M	L
Social (C_3)	Safety (C_{31})	B	AH	AH	VH
	Health (C_{32})	B	AH	AH	VH
	Quality of life (C_{33})	B	VH	VH	H
	Impact on business services (C_{34})	B	MH	H	MH
	Impact on community services (C_{35})	B	H	H	MH

The absolute fuzzy anti-ideal point, denoted as $\tilde{\alpha}_{AIP}$, is determined by its value of (0.5, 0.5, 0.5).

By employing Eq. (1), one can calculate the fuzzy relation vectors. Furthermore, an illustrative instance of calculating fuzzy vectors for DM_1 is also provided.

$$\tilde{\rho}^1_{C_{11}} = (\frac{4}{0.5}, \frac{4.5}{0.5}, \frac{5}{0.5}) = (8,9,10) \qquad \tilde{\rho}^1_{C_{23}} = (\frac{3}{0.5}, \frac{3.5}{0.5}, \frac{4}{0.5}) = (6,7,8) \qquad \tilde{\rho}^1_{C_{31}} = (\frac{4.5}{0.5}, \frac{5}{0.5}, \frac{5}{0.5}) = (9,10,10)$$

$\tilde{\rho}^1_{C_{12}} = (\frac{3}{0.5}, \frac{3.5}{0.5}, \frac{4}{0.5}) = (6,7,8)$ $\tilde{\rho}^1_{C_{24}} = (\frac{3.5}{0.5}, \frac{4}{0.5}, \frac{4.5}{0.5}) = (7,8,9)$ $\tilde{\rho}^1_{C_{32}} = (\frac{4.5}{0.5}, \frac{5}{0.5}, \frac{5}{0.5}) = (9,10,10)$

$\tilde{\rho}^1_{C_{13}} = (\frac{2.5}{0.5}, \frac{3}{0.5}, \frac{3.5}{0.5}) = (5,6,7)$ $\tilde{\rho}^1_{C_{25}} = (\frac{3}{0.5}, \frac{3.5}{0.5}, \frac{4}{0.5}) = (6,7,8)$ $\tilde{\rho}^1_{C_{33}} = (\frac{4}{0.5}, \frac{4.5}{0.5}, \frac{5}{0.5}) = (8,9,10)$

$\tilde{\rho}^1_{C_{14}} = (\frac{3}{0.5}, \frac{3.5}{0.5}, \frac{4}{0.5}) = (6,7,8)$ $\tilde{\rho}^1_{C_{26}} = (\frac{2.5}{0.5}, \frac{3}{0.5}, \frac{3.5}{0.5}) = (5,6,7)$ $\tilde{\rho}^1_{C_{34}} = (\frac{3}{0.5}, \frac{3.5}{0.5}, \frac{4}{0.5}) = (6,7,8)$

$\tilde{\rho}^1_{C_{15}} = (\frac{2.5}{0.5}, \frac{3}{0.5}, \frac{3.5}{0.5}) = (5,6,7)$ $\tilde{\rho}^1_{C_{27}} = (\frac{4.5}{0.5}, \frac{5}{0.5}, \frac{5}{0.5}) = (9,10,10)$ $\tilde{\rho}^1_{C_{35}} = (\frac{3.5}{0.5}, \frac{4}{0.5}, \frac{4.5}{0.5}) = (7,8,9)$

$\tilde{\rho}^1_{C_{21}} = (\frac{4}{0.5}, \frac{4.5}{0.5}, \frac{5}{0.5}) = (8,9,10)$ $\tilde{\rho}^1_{C_{28}} = (\frac{4}{0.5}, \frac{4.5}{0.5}, \frac{5}{0.5}) = (8,9,10)$

$\tilde{\rho}^1_{C_{22}} = (\frac{4.5}{0.5}, \frac{5}{0.5}, \frac{5}{0.5}) = (9,10,10)$ $\tilde{\rho}^1_{C_{29}} = (\frac{1}{0.5}, \frac{1}{0.5}, \frac{1}{0.5}) = (2,2,2)$

The computation is done similarly for other experts. The resulting fuzzy relation vectors are as follows:

$$\tilde{R}^2 = \begin{Bmatrix} (7,8,9),(6,7,8),(5,6,7),(6,7,8),(7,8,9),(8,9,10),(8,9,10),(9,10,10),(9,10,10),(8,9,10) \\ (7,8,9),(8,9,10),(7,8,9),(5,6,7),(9,10,10),(9,10,10),(8,9,10),(7,8,9),(7,8,9) \end{Bmatrix}$$

$$\tilde{R}^3 = \begin{Bmatrix} (8,9,10),(5,6,7),(5,6,7),(6,7,8),(7,8,9),(6,7,8),(6,7,8),(8,9,10),(8,9,10),(7,8,9) \\ (5,6,7),(6,7,8),(5,6,7),(3,4,5),(8,9,10),(8,9,10),(7,8,9),(6,7,8),(6,7,8) \end{Bmatrix}$$

The vector of weight coefficients is determined using Eq. (2). Below is an example of computing the vector of weight coefficients for DM_1 based on the first criterion.

$$\tilde{w}^1_{C_{11}} = \begin{pmatrix} \dfrac{\ln(8)}{\ln(10\times8\times7\times8\times7\times10\times10\times8\times9\times8\times7\times10\times10\times2\times10\times10\times10\times8\times9}, \\ \dfrac{\ln(9)}{\ln(9\times7\times6\times7\times6\times9\times10\times7\times8\times7\times6\times10\times9\times2\times10\times10\times9\times7\times8}, \\ \dfrac{\ln(10)}{\ln(8\times6\times5\times6\times5\times8\times9\times6\times7\times6\times5\times9\times8\times2\times9\times9\times8\times6\times7} \end{pmatrix} = (0.052, 0.058, 0.065)$$

Experts compute the weight coefficients of criteria similarly. The computed values of these coefficients are presented below.

$$w^1_j = \begin{Bmatrix} (0.052,0.058,0.065),(0.045,0.051,0.059),(0.040,0.047,0.055),(0.045,0.051,0.059),(0.040,0.047,0.055), \\ (0.052,0.058,0.065),(0.055,0.061,0.065),(0.045,0.051,0.059),(0.049,0.055,0.062),(0.045,0.051,0.059), \\ (0.040,0.047,0.055),(0.055,0.061,0.065),(0.052,0.058,0.065),(0.017,0.018,0.020),(0.055,0.061,0.065), \\ (0.055,0.061,0.065),(0.052,0.058,0.065),(0.045,0.051,0.059),(0.049,0.055,0.062) \end{Bmatrix}$$

Perform a similar process based on the expert's judgments for the remaining criteria.

Eq. (3) is utilized to calculate aggregated fuzzy vectors of the weight coefficients. Hereafter, an illustration of the aggregation of the vector of weight coefficients for criterion C_{11} is presented.

$$\tilde{w}_1 = \begin{Bmatrix} (\frac{1}{3(3-1)} 0.052\times0.046+0.052\times0.052+0.046\times0.052+0.052\times0.052+0.052\times0.052+0.052\times0.046)^{\frac{1}{1+1}}, \\ (\frac{1}{3(3-1)} 0.058\times0.052+0.058\times0.059+0.052\times0.058+0.052\times0.059+0.059\times0.058+0.059\times0.052)^{\frac{1}{1+1}}, \\ (\frac{1}{3(3-1)} 0.065\times0.058+0.065\times0.067+0.058\times0.065+0.058\times0.067+0.067\times0.065+0.067\times0.058)^{\frac{1}{1+1}} \end{Bmatrix}$$

$$\tilde{w}_1 = (0.050, 0.056, 0.063)$$

Values are computed using a similar approach. The following are the aggregated fuzzy weight coefficient vectors.

$$\tilde{w}_j = \begin{Bmatrix} (0.050,0.056,0.063),(0.043,0.049,0.057),(0.040,0.047,0.054),(0.044,0.051,0.058),(0.045,0.051,0.059), \\ (0.049,0.055,0.062),(0.050,0.056,0.062),(0.050,0.056,0.062),(0.051,0.057,0.063),(0.048,0.054,0.061), \\ (0.042,0.049,0.057),(0.050,0.056,0.062),(0.046,0.052,0.060),(0.027,0.032,0.038),(0.053,0.059,0.064), \\ (0.053,0.059,0.064),(0.050,0.056,0.063),(0.045,0.052,0.059),(0.047,0.053,0.060) \end{Bmatrix}$$

The weight coefficients are acquired through defuzzification, using Eq. (4). An illustration of the calculation of the weight coefficient for criterion C_{11} is presented:

$$w_{C_1} = \frac{0.050+4\times0.056+0.063}{6} = 0.056$$

Other values are derived in a comparable manner. The finalized weight coefficient values are as follows in Table 6 and Fig. 3:

Table 6
Finalized weight coefficients values for each criterion

Symbol	Weight coefficients	Rank
C_{11}	0.056	4
C_{12}	0.049	16
C_{13}	0.047	18
C_{14}	0.051	15
C_{15}	0.052	14
C_{21}	0.055	9
C_{22}	0.056	6
C_{23}	0.056	8
C_{24}	0.057	3
C_{25}	0.054	10
C_{26}	0.049	17
C_{27}	0.056	6
C_{28}	0.053	12
C_{29}	0.032	19
C_{31}	0.059	1
C_{32}	0.059	1
C_{33}	0.056	5
C_{34}	0.052	13
C_{35}	0.053	11

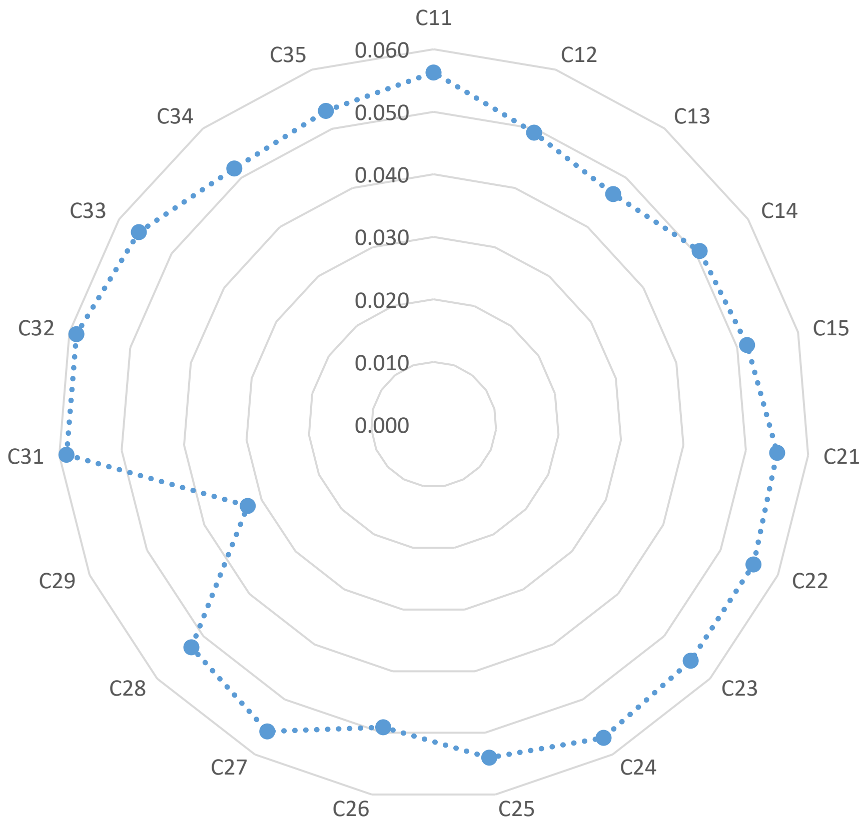

Fig. 3. Illustration of sustainable transportation key criteria weight coefficient

6. Analysis of Results

The methodology and study results allow a vital understanding of prioritizing key elements of sustainable transportation through economic, environmental, and social factor assessment. Sustainable transportation systems depend heavily on safety (C_{31}) and health (C_{32}) since these factors received the top-ranking position (1st) according to the results. The methodology supports global sustainability frameworks such as the United Nations Sustainable Development Goals since they promote human well-being with safe urban environments. The high ranking of greenhouse gas emissions (C_{24}, 3rd) further reflects the growing recognition of climate change mitigation as a basis of sustainable transportation, resonating with international agreements like the Paris Accord.

Although infrastructure/project development cost (C_{11}, 4th) emerged as a significant economic barrier, other financial factors- operating cost (C_{12}, 16th), time cost (C_{13}, 18th), and maintenance cost (C_{14}, 15th)-were deprioritized. The stakeholders appear to prioritize capital expenditures over long-term operational costs, possibly due to funding limitations within budget cycles or because visible infrastructure projects appeal to political motivations. Disregarding operating and maintenance expenses creates lifecycle sustainability problems as it threatens systems' long-term operational efficiency. Alongside greenhouse gas emissions, sustainability indices received moderate attention with respect to resource use and renewable fraction functions. Addressing noise pollution and landscape degradation appears to be a lower priority since these environmental concerns ranked lower compared to other categories (C_{26}, 17th, and C_{28}, 12th). Public support for sustainability projects faces challenges due to decision-makers ignoring visual negative effects (rank C_{29} at 19th place).

Transportation systems maintain an important relationship with social equity and accessibility because quality of life ranks as the 5th most important factor (C_{33}), and community service impact stands at position 11 (C_{35}). Potential institutional weaknesses exist in sustainability frameworks because businesses rank lower than other stakeholders (C_{34}, 13th) regarding their impact on business services.

7. Discussion

The research outcomes of this study have significant implications for transportation planning that promotes sustainability as they address the needs of the growing urban populations amid changing environmental conditions and evolving public demands. The study ranks 19 criteria according to economic, environmental, and social dimensions and demonstrates both global sustainability compatibility and identification of present planning framework deficiencies. The following section elaborates on these implications by integrating academic literature along with policy barriers and their applicable solutions. The foremost implication of this study is the need for planners and policymakers to adopt integrated, and systemic approaches that harmonize economic, environmental, and social priorities. The rankings reveal inherent tensions between short-term economic concerns (e.g., infrastructure costs) and long-term environmental goals (e.g., emissions reduction). For instance, while infrastructure development cost (C_{11}) ranks 4th, its prioritization over operating costs (C_{12}, 16th) and maintenance costs (C_{14}, 15th), it risks creating “lock-in” effects, where low upfront investments lead to higher lifecycle expenses or environmental degradation. This aligns with traditional cost-benefit analyses (CBA) perspectives, which often undervalue externalities such as air pollution or health impacts [69].

A holistic approach demands frameworks such as Triple Bottom Line (TBL), which evaluates projects based on their social, environmental, and economic performance [69]. For example, a highway expansion may reduce travel time (economic benefit) but exacerbate emissions and noise pollution (environmental/social costs). Results show that practitioners weakly assess negative visual effects (C_{29}, 19th) and noise pollution (C_{26}, 17th) despite their impact on community health and satisfaction. Planners’ adoption of MCDA tools provides quantitative methods for criterion trade-off assessment to prevent any individual aspect from controlling decision-making (World Health Organization, 2023). Human-centric transportation systems emerge due to safety (C_{31}) and health (C_{32}) sharing a top-ranking position in the priorities. The World Health Organization (WHO) predicts that safer infrastructure has the potential to reduce annual traffic fatalities by 1.3 million, and these trends match national strategies. Premature death risk reductions from air pollution, which trigger 7 million fatalities each year, have become the leading focus of urban policy [70]. Nonetheless, despite safety’s top priority, the low ranking of accident costs (C_{15}, 14th) reveals a dissonance between qualitative and quantitative assessments. Policymakers must reconcile this by embedding safety metrics (e.g., fatalities per capita) into economic models, ensuring that accident prevention is valued as highly as infrastructure savings.

Greenhouse gas emissions receive a top priority (C_{24}, 3rd), as the transportation industry plays a crucial part in climate mitigation through its emission contribution of 24% CO_2 [70]. However, the moderate ranking of renewable fraction (C_{23}, 8th) signals an under appreciation of energy source sustainability. The transition to renewable energy systems requires solutions for two main problems, which include fossil fuel subsidy structures and power grid flexibility limits. Policymakers must adopt carbon pricing mechanisms (cap-and-trade systems) to internalize emissions costs and incentivize clean energy adoption.

Despite their mid-tier rankings, the prominence of operating costs (C_{12}) and maintenance costs (C_{14}) highlights the need for long-term fiscal sustainability. Many transportation projects fail due to “build-neglect-rebuild” cycles, where deferred maintenance escalates costs over time [71]. The low ranking of time cost (C_{13}, 18th) is paradoxical, given that, for instance, congestion costs the U.S. economy $190 billion annually [72]. This discrepancy may stem from methodological biases (e.g., valuing aggregate savings over individual delays) or political reluctance to implement congestion pricing. Additional investigations are required to investigate environmental elements that affect perceptions of time value in services. The study recommends inclusive stakeholder participation to handle the different priorities identified through the rankings. The monetary values placed on the quality of life (C_{33}, 5th) and community services (C_{35}, 11th) are moderate. However, planning procedures frequently overlook participation from marginalized social groups like low-income residents. However, the low ranking of business services impact (C_{34}, 13th) suggests that private sector priorities are often sidelined. Planners must balance community needs with economic vitality by fostering freight-friendly infrastructure and last-mile delivery hubs, as exemplified by Rotterdam's "City Logistics" program [73].

7.1. Integrating Emerging Criteria in Sustainable Transportation Planning

Five new criteria, including Public-Private Partnerships (PPPs), waste reduction, and support for local and global economies, have strengthened the sustainable transportation system assessment framework. The evaluation criteria stem from expert analysis and post-study survey data to fill the gaps in previous sustainability frameworks, thus reflecting modern transportation planning goals. These new criteria receive further analysis concerning academic and professional practice by defining their theoretical underpinnings, real-world applications, and policy impacts.

7.1.1. Public-Private Partnerships (PPPs): Bridging Funding and Innovation Gaps

The new criterion of PPPs demonstrates increasing awareness about collaborative governance for sustainable infrastructure development. According to Ostrom's academic principles, multiple stakeholders should have shared governance of resources to improve operational success and achieve fair outcomes [74]. Practically, PPPs mitigate fiscal constraints by leveraging private sector capital and expertise, as seen in Canada's Highway 407 ETR, where toll revenues fund maintenance without public expenditure [75]. Strong regulatory systems protect PPPs from problems with escalating costs combined with unbalanced service prices [76]. For instance, the failure of Melbourne's privatized rail system, marked by service cuts and public backlash, highlights the need for transparency and accountability [77].

7.1.2. Waste Reduction: Toward Circular Transportation Systems

When waste reduction occurs, the circular economy gains central status as a sustainability measurement point. Theoretical applications match Stahel's "cradle-to-cradle" model, which minimizes resource extraction and landfill dependency [78]. The practical operation of transportation systems produces waste through building debris, such as asphalt and concrete, alongside retired vehicles. The circular tram network of Amsterdam demonstrates sustainable recycling through its efficient approach to reusing retired railway materials to the extent of 97 percent [79].

7.1.3. Support for Local and Global Economy: Balancing Scale and Equity

This criterion challenges planners to reconcile local economic vitality with global supply chain efficiencies. Academically, it resonates with Porter's "shared value" theory, where economic growth aligns with societal needs [80]. Locally, transit-oriented development (TOD) investments can stimulate small businesses, as demonstrated by Portland's Streetcar Corridor, which boosted retail revenue by 60% [81]. Globally, efficient freight corridors-like China's Belt and Road Initiative-enhance trade but risk exacerbating regional disparities [82].

7.1.4. Public Awareness and Behavior Change: The Human Dimension of Sustainability

Public awareness and behavior change emphasize the role of societal norms in achieving sustainability goals. Theoretically, this aligns with Ajzen's Theory of Planned Behavior, where attitudes and perceived control shape actions [83]. Practically, Copenhagen's cycling culture, supported by decades of awareness campaigns, shows how societal shifts can reduce car dependency [84]. Conversely, India's stalled electric vehicle (EV) adoption, despite subsidies, reveals gaps in public education about charging infrastructure [85,86].

7.1.5. User Satisfaction and Comfort: Beyond Functional Utility

User satisfaction and comfort elevate subjective well-being to a measurable sustainability outcome. Academically, this reflects Maslow's hierarchy of needs, where comfort and safety are foundational to human motivation [87]. In practice, Japan's Shinkansen trains- prioritizing punctuality, cleanliness, and ergonomic seating- boast 95% user satisfaction, driving high ridership despite premium pricing [88]. The poor conditions of overcrowded buses in Jakarta, which are the most uncomfortable system, have led people to shift away from public transportation [89].

7.2. Synthesizing New and Existing Criteria

These assessment criteria complicate sustainability assessments while delivering greater depth to the evaluations. For example, the efficiency of private sector operations through PPPs helps reduce future operating expenses, which corresponds to C_{12}. Between them, waste reduction and resource use (C_{22}) create a circular economy that succeeds when they work together. Sustainable practices influence quality of life (C_{33}) because satisfaction among users elevates the general quality of life. The decision to support local economies produces friction with global supply chain optimization because it necessitates performing trade-off evaluations. Budgetary needs for public awareness campaigns create a potential funding challenge for infrastructure costs (C_{11}).

8. Conclusion, Limitations, and Future Research

This research develops a fuzzy-based MCDA method for sustainability criterion assessment in transportation decision-making processes. Through the incorporation of F-LMAW, the research implemented an efficient approach for prioritizing sustainability factors under the economic, environmental, and social dimensions. Safety, health conditions, and emissions of greenhouse gases, emerged as the most important criteria from the results while demonstrating the need to strike a balance between economic feasibility and human safety and environmental protection. Research findings show that F-LMAW operates as a digitally stable option that replaces conventional MCDA procedures. LMAW achieves weight determination consistency through reliable procedures while removing issues of rank reversal and data sensitivity that affect TOPSIS and AHP. The incorporation of fuzzy numbers in this study enables the methodology to handle expert assessment uncertainty, which makes it more suitable for solving real-world transportation problems. Sustainable transportation planning advances through research since it provides structured data-driven methods that enable policymakers and urban planners to make informed decisions on investment prioritization and resource optimization while minimizing environmental consequences. Based on these findings, this work lays the foundation for future research by demonstrating the suitability fuzzy-enhanced MCDA methods in sustainability evaluation processes.

This evaluation framework benefits from mathematical robustness and structure to analyze sustainable transportation criteria. However, it still requires to address a number of limitations. The evaluation criteria show generalization issues as they are applied across all geographic areas. Future investigations of F-LMAW methodology must implement research in specific locations, spanning different regions, economic systems, and policy structures. The proposed methodology needs validation through specific context analysis to increase authenticity. The application of this study uses a limited selection of fixed sustainability criteria as evaluation criteria. This study includes economic, environmental, and social pillars of sustainability, yet faces potential future sustainability challenges due to advancements in smart mobility, autonomous transportation, and emerging green technologies. Future research initiatives need to expand the framework by implementing new sustainability criteria that correspond to recent advancements in the transportation sector including digitalization, and energy-efficient transport systems. Additional assessment of F-LMAW against fuzzy BWM and its counterparts such as fuzzy WASPAS and Z-fuzzy extensions could strengthen the methodological validation of this approach. Moreover, deviations between experts remain untested through direct statistical measures. Deep investigative research into F-LMAW compared to different decision-making systems will create enhanced knowledge about its useful applications and system enhancement potential. This research uses expert evaluations for assessing sustainability, which delivers value but adds subjectivity to the evaluation process.

Future studies should link real-time transport information systems with machine learning models for continuously determining sustainability elements. Transportation planning professionals use big data analytics and AI-driven decision support systems, which enable the development of adaptive, predictive, evidence-based decision-making tools to improve their sustainability evaluations. The practicality with which fuzzy-based sustainable transportation evaluation models function can be improved through the inclusion of regional case studies and broad sustainability criteria, multiple criteria decision-making analysis, as well as with real-time data. The progress of sustainable mobility relies heavily on developing improved approaches, which lead to data-driven transportation policies that support future requirements.

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Conflicts of Interest
The authors declare no conflicts of interest.

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