



Robust Multicriteria Sustainability Assessment in Urban Transportation

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Abstract: Developing methodologies to facilitate the planning of sustainable transport systems for decision makers (DMs) is becoming more critical. This study proposed a methodological framework for sustainable urban transportation to make decisions during urban transportation's design and planning stages. Urban transportation alternatives were evaluated by sustainability indicators that considered a triple bottom line approach's environmental, economic, and social aspects. To choose the best alternative sustainable transportation scenarios, two multicriteria decision-making (MCDM) methods, for example, a hesitant fuzzy analytical hierarchy process (HF-AHP) and multiple attribute utility model (MAUT), were integrated. First, eight sustainable transportation indicators that considered data availability from the transport sector were selected. The weights of the selected indicators were calculated using an HF-AHP. These indicators included carbon dioxide (CO₂) emissions, energy consumption, depletion of nonrenewable resources, operational and maintenance costs, fuel and taxes, the number of fatalities or injuries, and motor vehicles for public transport per 10,000 population. Finally, sensitivity analysis was applied to validate the robustness. Based on HF-AHP results, the number of fatalities or injuries was the most significant among the eight indicators, with a 0.158 normalized weight (N_i). The results of this integrated methodology highlighted that Alternative 11, which was dominated by low-motorized vehicles (low-MVs), was the best sustainable alternative and Alternative 1 was the worst sustainable alternative, which was dominated by high-MVs with 0.69 and 0.27 total utility values, respectively. Low-motorized urban transportation alternatives showed higher sustainable performances than the motorized and high-motorized alternatives. This study proposed a novel and robust methodology for decisions on sustainable urban transportation projects and renovating current urban transportation systems. DOI: 10.1061/JUPDDM.UPENG-4090. © 2023 American Society of Civil Engineers.

Author keywords: Hesitant fuzzy analytical hierarchy process; Multiple attribute utility models; Multicriteria decision making; Sustainable transportation.

Introduction

Sustainable transportation, which is one of the major elements in sustainable development (Batur et al. 2019), is defined as transportation which meets the needs for access without damaging the ecosystem and human health by the Organisation for Economic Co-operation and Development (OECD) (The Institution of Engineers Australia 1999). The term covers the economic, social, and environmental aspects of transportation that considers its benefits to people, the planet, and profit for the triple bottom line. The concentration of people in urban areas increases the demand for primary goods and services, such as food, energy and transport, and fulfilling these demands results in substantial carbon emissions (Penazzi et al. 2019). To measure sustainability in transportation systems that have several aspects, the use of indicators has become necessary. Sustainable indicators are essential tools that convert

a high volume of information into a simple, clear, and understandable form. However, a standard sustainable indicator system for transportation does not exist due to disagreements on the definition of sustainability and different aims when establishing a framework (Wang 2014). In addition, research into sustainable transportation has yielded enough indicators. In these studies, various indicator indexes were constructed to measure the sustainability of the transportation system in selected areas.

Passenger and freight transportation are the two primary subcategories of urban transportation. The movement and activities that are caused by freight activity in urban settings are referred to as urban freight transportation. The global increase in online sales and e-commerce has significantly increased the demand for product deliveries in metropolitan regions (Li et al. 2021). Despite the global development of urban freight transportation, urban freight has certain logistical problems. For instance, there are numerous stakeholders in urban logistic businesses. However, when considering potential solutions to problems that were caused by freight operations, planners and decision makers (DMs) frequently overlooked these stakeholders (Amaya et al. 2021). Another issue is that urban logistics are becoming increasingly complicated and expensive. The increase in e-commerce, customer expectations, the drive to improve delivery performance when cutting costs, and advances in a city or urban sustainability and quality of life are some of the reasons (Comi and Savchenko 2021). In urban passenger transportation planning, the share of motorized and nonmotorized urban transportation modes has a significant role in sustainability. Walking and biking, which are the main nonmotorized transport modes, are cheaper, more environmentally friendly, and moderately fast for trips ≤ 3.5 km compared with motorized transport

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Note. This manuscript was submitted on March 4, 2022; approved on January 25, 2023; published online on April 10, 2023. Discussion period open until September 10, 2023; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Urban Planning and Development*, © ASCE, ISSN 0733-9488.

modes (Rietveld 2000). For longer distances, motorized transport modes, such as buses, tramways, and light rail systems, are required for effective and comfortable urban passenger transportation. However, motorized transport modes are more expensive and less environmentally friendly. Therefore, the use of nonmotorized and motorized transport modes significantly affects the sustainability of urban transportation systems. Depending on the transportation demand for one-way journeys during rush hours, urban passenger transportation modes might vary in cities. In addition, the length of the line and the number of vehicles for public transportation are significant parameters in urban transportation planning for accessibility. In addition to these parameters, environmental, economic, and social indicators should be considered for sustainable urban transportation. Therefore, urban transportation modes should be optimized and integrated when the triple bottom line approach is considered.

For sustainable transport planning, a comprehensive decision-making process is required. Transport plans or scenarios are partially sustainable with limited environmental and economic points of view. These views should be integrated and optimized to make transport plans or scenarios more sustainable with the help of effective decision-making, which is a process that chooses the best from several alternatives (Tupenaite et al. 2010). Therefore, multicriteria decision-making (MCDM) methods have a significant impact when the best alternative is chosen. For the evaluation of sustainable transport strategies in Taiwan, Shiau and Liu (2013) proposed an indicator system with an evaluation of 21 indicators. Based on the results, the emission intensity of greenhouse gases (GHGs) was the most important indicator when an analytical hierarchy process (AHP) was used. In addition, Erdoğan and Kaya (2019) proposed a hybrid MCDM methodology that was composed of type-2 fuzzy AHP (F-AHP) and technique for order preference by similarity to ideal solution (TOPSIS) methods and applied it to a bus rapid transit (BRT) system in Istanbul, Türkiye. Based on five criteria, 17 alternatives were evaluated, and the cost of failure had the highest score of 0.544, and repair time had the lowest score of 0.093. Erdoğan and Kaya (2020) suggested a systematic approach, which covered a fuzzy rule-based system (FRBS) and fuzzy MCDM to assess the risks and failure in public transport systems. The proposed approach was implemented on the BRT system in Istanbul, and 15 failure types that were based on five vehicle models were evaluated. The proposed system (i.e., based on FRBS) worked with 80% accuracy (Erdoğan and Kaya 2020). Chow et al. (2013) studied sustainable assessment in transport planning for recreational travel with multicriteria aspects. Their study applied a composite sustainability index (CSI) to assess eight alternatives under three decision-making schemes. However, social sustainability was excluded from their study because of a lack of data. By considering the environmental, economic and social dimensions, Emrouznejad et al. (2019) proposed a framework that was based on the best worst method for the evaluation of the sustainability criteria in an urban transportation network. Their model was applied to a case study on transportation in Isfahan, Iran. The research team selected 17 criteria that were divided into three groups: (1) social; (2) economic; and (3) environmental. Community cohesion, transportation cost for governments, and land consumption were the worst criteria in the social, economic, and environmental categories, respectively (Mahmoudi et al. 2019). In the literature, some researchers studied sustainable transportation to evaluate transportation systems from several aspects (e.g., environmental, economic, or social) that considered various indicators (Shiau and Liu 2013; Chow et al. 2013; Mahmoudi et al. 2019; Zope et al. 2019; Wang 2014). However, studies on sustainable urban transportation with a holistic and robust framework that considered the triple bottom line approach are limited. In addition, some researchers studied MCDM methodologies (e.g., AHP,

F-AHP, and TOPSIS) for sustainable transportation. However, to the best of the authors' knowledge, no integrated methodology for hesitant fuzzy analytical hierarchy processes (HF-AHP) and multiple attribute utility models (MAUT) for sustainable transportation exist in the literature. This study could contribute to fill this research gap by providing a new integrated methodology (i.e., HF-AHP and MAUT) in sustainable transportation that considers a triple bottom approach with a holistic and comprehensive evaluation.

Decision-making is not an easy and simple process, because individuals are hesitant and irresolute, which makes it hard to obtain a final agreement (Xu 2014). Uncertainty of real-world problems brings about to originate new methodologies and theories to deal these problems. In decision-making problems, attributes are not usually represented by real numbers; some of them are expressed with fuzzy values as: (1) interval values (Cao and Wu 2011; Xu 2004), in which the membership degree of an element is introduced by a closed subinterval of the unit interval; (2) fuzzy numbers (Xu and Chen 2007), where the membership degree of each element varies between zero and one; (3) hesitant fuzzy elements (Zhu et al. 2012; Xu and Xia 2011a, 2011b), which describe the situations that permit the membership of an element to a given set that has a few different values; and (4) intuitionistic fuzzy numbers (Xu 2012; Xu and Yager 2006), that allow the membership degree to be simultaneously considered.

Fuzzy sets are useful tools that deal with uncertainty in several problems. Recently, hesitant fuzzy sets (HFSs), which are a new extension of fuzzy sets, have attracted attention from researchers to deal with hesitant situations (Rodríguez et al. 2014). The preference information from eight DMs was used to decide the best from 12 alternatives. DMs are usually unsure of a preference's exact value, but have hesitancy about a range of possible values; therefore, they judge the extent to which an alternative should fulfill an attribute (Xia and Xu 2012). Therefore, HFSs were utilized to obtain more reasonable decision results due to the hesitancy of the preferences of DMs in their study.

This study integrates two decision-making strategies (e.g., HF-AHP and MAUT) to choose the best alternative sustainable passenger transportation scenarios. Eight sustainable transportation indicators will be used for a city with a population of >1 million. First, eight indicators [(i.e., criteria), three environmental, three economic, and two social] are selected from 82 indicators that considered data availability from the transport sector. Second, HF-AHP is utilized to determine the weights of the selected sustainable transport indicators. Finally, the MAUT is used to select the best alternative from the three predetermined urban passenger transportation scenarios. To the best of our knowledge, studies on sustainable urban transportation that consider MCDM with a holistic approach are limited in the literature. In addition, sensitivity analysis is applied to fulfill the effective robustness by exchanging each criterion weight with another. This study presents a novel and robust methodology for sustainable urban passenger transportation systems that encourage DMs to holistically assess the environmental, economic, and social components in urban transportation planning.

Methodology

The model that was proposed to measure the sustainability of alternative transportation scenarios was composed of integrated HF-AHP and MAUT methods. It was composed of three critical stages: (1) preprocessing; (2) HF-AHP; and (3) MAUT. The new model for sustainable transportation measurement is shown in Fig. 1.

The proposed model was applied to urban passenger transportation in Kayseri. The urban passenger transportation in Kayseri

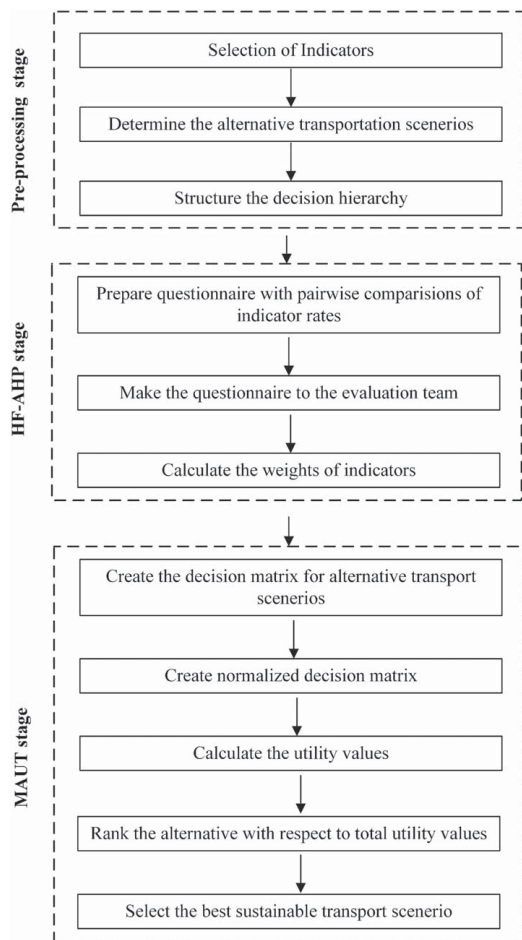


Fig. 1. Proposed model approach.

included buses, tramways, and bicycle systems. The urban passenger transportation system offers 613 buses and 318 bus lines, 55 tramway stations with 34 km of tramway lines, and 600 bicycles with 51 bicycle stations. Kayseri Transportation, Türkiye reported that the annual bus passenger numbers were >92 million in 2019 and >48 million in 2020. In addition, the annual number of passengers on the tramway was >40 million in 2019 and >23 million in 2020 (Kayseri 2022).

Preprocessing Stage

Measuring the sustainability of urban transport is crucial in planning and managing urban transport systems, evidenced by a significant number of studies (Reisi et al. 2014; Nicolas et al. 2003; Shiau and Liu 2013). In the first part of this study, the list of sustainable transport indicators from the literature was compiled (Table 1). The 82 indicators were classified into three main groups: (1) environmental; (2) economic; and (3) social, as listed in Table 1.

The selection of a set of indicators was a significant and challenging process. Utilizing a smaller set of indicators was more suitable; however, it could neglect some essential items. In addition, the use of a growing number of indicator sets was more comprehensive. However, their collection and analysis costs were more expensive and time-consuming. Therefore, the selection of the indicators should be optimized by considering the availability of relevant, qualitative, precise, and comparable data (Zope et al. 2019). Therefore, sustainable transportation indicators were selected based on the availability of relevant and reliable data in this study. The

selected sustainable transport indicators for the environmental, economic, and social aspects for the evaluation of the alternative transport scenarios are given in Table 2.

HF-AHP

Thomas L. Saaty developed an MCDM method that was called the AHP (Saaty 1980). This method provided a model for complex problems with a hierarchical structure that split them into small and solvable problems. The hierarchy indicated the relationships between the goals, objectives, and alternatives. The AHP method covered pairwise comparisons, the hierarchical structure of complexity, judgments that considered the aim and criteria, and an eigenvector method to obtain the weights (Oztaysi et al. 2015).

Several researchers proposed the use of AHP methods for the selection of alternatives systematically, which used the fuzzy set theory and concept of hierarchical structure. The DMs usually preferred this method, because they found that it provided better interval judgments than fixed value judgments. Another reason this method was preferred was because it could not make explicit preferences due to the fuzziness of the comparison process (Oztaysi et al. 2015).

A HFS is a valuable tool for uncertainty and hesitant situations. It helps to decide evaluations under a set for DMs. With the HF-AHP, evaluations from DMs for comparison matrixes were demonstrated by linguistic variables. Then, the judgments of DMs were combined with the hesitant fuzzy geometric operator (Mousavi et al. 2014).

HFSs are an extension of the fuzzy set theory that was first presented by Torra (2010) and Torra and Narukawa (2009). Membership degrees of an element must be stated as set to use HFSs. This desired element is called a hesitant fuzzy element, which is defined as a set of possible values. Therefore, DMs could manage a hesitant situation by specifying their judgments under a set (Mousavi et al. 2014).

HFSs: Preliminaries

This section will describe some basic definitions of HFS concepts and describe some operations.

Definition 1 (Xia and Xu 2011)

Let X be a fixed set, then the HFS was defined as E on X in terms of a function $h_E(x)$, which was applied to X returns E under $[0, 1]$. The mathematical expression for the HFS is

$$E = \{x, h_E(x) | x \in X\} \quad (1)$$

where $h_E(x)$ = possible membership degrees of the element $x \in X$ to the set E in $[0, 1]$; and $h_E(x)$ = hesitant fuzzy element for convenience.

Definition 2 (Torra 2010; Torra and Narukawa 2009)

Some basic operators are described as follows:

$$h^-(x) = \min h(x) \quad (2)$$

$$h^+(x) = \max h(x) \quad (3)$$

$$h_a^+ = \{h \in h(x) | h \geq \alpha\} \quad (4)$$

$$h_a^- = \{h \in h(x) | h \leq \alpha\} \quad (5)$$

$$h^c(x) = \cup_{\gamma = h(x)} \{1 - \gamma\} \quad (6)$$

$$(h_1 \cup h_2)(x) = \{h \in (h_1(x) \cup h_2(x)) | h \geq \max(h_1^-, h_2^-)\} \quad (7)$$

Table 1. List of sustainable transportation indicators from literature

References	Environmental indicators	Economic indicators	Social indicators
Reisi et al. (2014)	Depletion of nonrenewable resources GHG emissions (tCO ₂ e) Other air pollutants [(carbon monoxide (CO), nitrogen dioxide (NO ₂), and PM10)] Land consumption for transport	Car ownership costs Vehicle and general cost of accidents	Accessibility Fatalities and injuries related to traffic accidents Mortality effects of air pollutants
Currie et al. (2018)	Quantity of energy consumed Mass of total pollutants emitted [e.g., nitrous oxides (NO _x), volatile organic compounds (VOCs), and CO ₂] Land area consumed by public transport facilities	Annual operating cost Cost recovery (proportion of costs recovered) Passenger km traveled per unit gross domestic product (GDP) Average time per trip	Travel participation Average user trip distance Affordability
Shiau (2012)	Emissions of air pollutants Noise perception	Transport intensity Energy intensity	Public transport related deaths Accessibility for disabled and aged 65 and over people Transport services for remote areas Traffic safety
Shiau and Liu (2013)	Proximity of transport infrastructure to designated environmentally sensitive areas (ESAs) Emission intensity of air pollutants Emission intensity of GHGs Recycling of used tires Recycling of end-of-life vehicles	Distribution density of transport Modal split of transit Service intensity of transit Loading factor of transit The ratio of parking lots for P&R The ratio of bus-exclusive lanes Modal split of nonmotorized modes Loading factor of private modes Truck loading factor Effect of public depot on freight transshipment	Traffic accidents Mobility and transport for older adults and people with disabilities Transport infrastructure in remote areas Transit subsidy in remote areas
Nicolas et al. (2003)	Annual energy consumption and CO ₂ emissions (total and per resident) Levels of CO, NO _x , hydrocarbons, and particles (g/m ² , total, and per resident) Daily individual consumption of public space involved in traveling and parking (m ² /h) Space taken up by transport infrastructures Noise intensity levels Risk of accident	Annual costs chargeable to residents for their mobility in a zone Annual average expenditures for urban mobility (per person/household) Company costs of employee parking, subsidies to employees (i.e., company cars) Annual public expenditures for investments and operations	Proportion of households owning 0, 1 or more cars Distance traveled Expenditure for urban mobility (e.g., amounts for private or public transport) Expenditures for urban mobility (i.e., share of the average income of households)
Zope et al. (2019)	PM10, SO ₂ , NO _x , and CO (t/year) CO ₂ (million t/year) Noise level (Db)	Population density motorized vehicles (MV) per 1,000 population Peak hour journey speed (km/h) Congestion index Per capita trip rate Average trip length (km)	Number of fatalities Serious injuries Percentage of trips by walking or cycle
Wang (2014)	Final petroleum products consumption of transport, storage, and post industry NO _x emissions from MV Percentage of land for transportation facilities Percentage of roads with excess noise	Ratio of expenditure on traffic to the total cash consumption expenditure for average individual Amount of standard operating motor vehicles Investment in fixed assets on transport, storage, and post industry Output value of transport, storage, and post industry	Number of traffic accidents Total loss to traffic accidents Motor vehicles for public transport per 10,000 population (standard unit)

$$(h_1 \cap h_2)(x) = \{h \in (h_1(x) \cap h_2(x)) | h \leq \min(h_1^+, h_2^+)\} \quad (8)$$

the following operation:

$$h(x) = [\mu_E(x), 1 - \nu_E(x)] \mu_E(x) \neq 1 - \nu_E(x) \quad (9)$$

where h , h_1 , and h_2 = HFSs.

Definition 3 (Torra 2010; Torra and Narukawa 2009)

All intuitionistic fuzzy sets (IFSs) are HFSs. Let the IFSs be denoted by $\{\langle x, \mu_E(x), \nu_E(x) \rangle\}$, then the HFS could be obtained by

Definition 4 (Xia and Xu 2011)

Then, h , h_1 , and h_2 were assumed to be three HFSs, and the primary operations on HFSs are given as follows:

Table 2. List of selected sustainable transportation indicators and units

Dimension	Indicator	Unit
Environmental	CO ₂ emissions (C1)	tCO ₂ e
	Energy consumption (C2)	MWh
	Depletion of nonrenewable resources (C3)	L
Economic	Operational costs (C4)	%
	Maintenance costs (C5)	%
	Fuel and taxes (C6)	%
Social	Number of fatalities or injuries (C7)	number
	Motor vehicles for public transport per 10,000 population (C8)	number

$$h^\lambda = \cup_{\gamma \in h} \{\gamma^\lambda\} \quad (10)$$

$$\lambda h = \cup_{\gamma \in h} \{1 - (1 - \gamma)^\lambda\} \quad (11)$$

$$\tilde{h}_1 \oplus \tilde{h}_2 = \cup_{\gamma_1 \in \tilde{h}_1, \gamma_2 \in \tilde{h}_2} \{\gamma_1 + \gamma_2 - \gamma_1 \gamma_2\} \quad (12)$$

$$\tilde{h}_1 \otimes \tilde{h}_2 = \cup_{\gamma_1 \in \tilde{h}_1, \gamma_2 \in \tilde{h}_2} \{\gamma_1 \gamma_2\} \quad (13)$$

$$\tilde{h}_1 \cup \tilde{h}_2 = \cup_{\gamma_1 \in \tilde{h}_1, \gamma_2 \in \tilde{h}_2} \max\{\gamma_1, \gamma_2\} \quad (14)$$

$$\tilde{h}_1 \cap \tilde{h}_2 = \cup_{\gamma_1 \in \tilde{h}_1, \gamma_2 \in \tilde{h}_2} \min\{\gamma_1, \gamma_2\} \quad (15)$$

MAUT

Keeney and Raiffa (1976) developed the MAUT. It evaluated DM preferences and modeled this mathematically with a multiple attribute utility function. This approach was based on the selection of a desirable alternative from various alternatives. It has been utilized in many fields, such as energy, manufacturing, public policy, health care, and fisheries (Keeney and Wood 1977).

With this method, the analysis of alternatives specified the measures, which were utilized to criticize the alternatives. In addition, it facilitated the identification of these alternatives that revealed the excellent performance for most of these measurements, which gave great importance to the measures that were considered more critical (Doczy and Abdelrazig 2017).

The MAUT was used to systematically identify and analyze multiple variables to obtain the desired decision. In this method, single utility functions and their weighting factors were the key elements to obtain multiattribute utility functions. Although several application procedures exist in theory and applications, they consist of five stages (Kim and Song 2009).

- Set the aim and establish the attributes for the purpose,
- Quantify the attributes,
- Derive the utility functions of each attribute,
- Calculate the weights of each attribute, and
- Derive multiattribute utility function.

Results and Discussion

Calculation of Weights of Indicators

In this study, the judgments of DMs, which included four academicians and four professionals from the transport sector, were represented by linguistic variables and their importance is given in Table 3.

Table 3. Hesitant linguistic terms and corresponding triangular fuzzy number

Hesitant linguistic variable	Triangular fuzzy numbers	Inverse triangular fuzzy numbers
Equally important (EI)	(1/2, 1, 3/2)	(2/3, 1, 2)
Less important (LI)	(1, 3/2, 2)	(1/2, 2/3, 1)
More important (MI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very important (VI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolute important (AI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Five different linguistic variables were used in this study. The steps in the HF-AHP for weight calculation were.

1. The linguistic term cluster $S = \{S_0, S_1, \dots, S_n\}$ was defined and used, as given in Table 3.
2. Pairwise comparison matrixes for criteria and evaluations by experts that used the linguistic terms were collected.
3. The env[d_{ij}] data envelop was constructed for each $i-j$ pair of criteria that contained linguistic terms, as given in Table 4.
4. The linguistic terms and corresponding triangular fuzzy numbers were identified.
5. The env[d_{ij}] data envelops were converted into the env[\tilde{d}_{ij}] data envelops that contained triangular fuzzy numbers.
6. The arithmetic mean of the fuzzy triangular numbers were calculated within the env[\tilde{d}_{ij}] data envelops, as given in Table 5.
7. The weight of the i th criterion were determined for the k th level by a geometric mean operation.
8. The fuzzy weights of each i th criterion with were calculated with

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \dots \oplus \tilde{r}_n)^{-1} \quad (lw_i, mw_i, uw_i) \quad (16)$$

where lw_i = lower weight of i th criteria; mw_i = medium weight of i th criteria; and uw_i = upper weight of i th criteria.

9. Compute final weights ($\sim w_i$) as follows (Table 6):

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \quad (17)$$

10. Normalization of fuzzy weights (M_i) for each i th criteria as follows (Table 6):

$$N_i = \frac{M_i}{\sum_{i=1}^n M_i} \quad (18)$$

The DMs stated their opinions when selecting a more sustainable urban transport scenario. Therefore, the evaluations of the DMs were used to establish the hesitant fuzzy linguistic comparison matrix for each $i-j$ pair of criteria, as given in Table 4. Then, the hesitant fuzzy linguistic comparison matrix was converted into the matrix with fuzzy triangular numbers for each $i-j$ pair of criteria. The arithmetic average was calculated for each pairwise comparison, as given in Table 5.

Then, the geometric means of fuzzy comparisons were calculated for each criterion's lower, medium, and upper values. Then, the M_i of each criterion were calculated with Eq. (1). The final weights of each criterion were calculated with Eq. (17), and the defuzzified M_i are given in Table 6. The final step in the HF-AHP method was the normalization of the weights. Each criterion's relative N_i were calculated with Eq. (3), and the values are given in Table 6. The results showed that several fatalities and injuries (C7) had the highest weight of 0.158, and MVs for public transport per 10,000 population (C8) had the lowest weight of 0.107.

Table 4. Envelope of linguistic terms for each $i-j$ pair of criteria

Criteria	C1	C2	C3	C4	C5	C6	C7	C8
C1	[EI]	[AI,MI,VI,AI,AI]	[AI,MI,MI,MI,VI, AI]	[MI,VI,MI]	[MI,MI,LI,AI,AI]	[MI,MI,MI,VI,VI]	—	[VI,MI,VI,LI,AI, MI]
C2	[LI,AI,VI]	[EI]	[LI,VI,AI]	[VI,MI,VI]	[VI,MI,LI,MI,VI, MI,VI]	[VI,MI,LI,VI]	—	[VI,MI,MI,VI,VI, AI,VI]
C3	[VI,MI]	[VI,MI,VI,VI]	[EI]	[LI,MI,LI,LI]	[LI,MI,LI,LI,MI]	[VI,MI,MI,MI]	—	[VI,MI,MI,VI,LI, VI]
C4	[VI,MI,VI]	[MI,MI,AI,VI,VI]	[VI,AI,VI,VI]	[EI]	[VI,MI,VI,LI,AI]	[VI,MI,MI,AI,MI]	[LI,LI]	[VI,MI,MI,VI,VI, VI]
C5	[MI,LI]	[MI]	[MI,MI,VI]	[MI,VI,VI]	[EI]	[LI,MI,VI,MI,VI]	—	[VI,MI,MI,AI,VI]
C6	[LI,VI]	[LI,VI,VI,VI]	[LI,VI,AI,VI]	[MI,LI]	[VI,AI,AI]	[EI]	[VI]	[LI,MI,LI,AI]
C7	[VI,AI,VI,LI,AI, AI,AI]	[VI,AI,VI,MI,LI, MI,MI]	[VI,AI,LI,LI,LI,AI, AI,AI]	[VI,AI,MI,AI, AI,AI]	[AI,AI,MI,MI,LI, AI,AI]	[AI,LI,MI,LI,AI, AI,AI]	[EI]	[AI,MI,VI,AI,AI, AI]
C8	[LI,MI]	[LI]	[VI,LI]	[MI]	[MI]	[VI]	[AI, MI]	[EI]

Table 5. Arithmetic averaged fuzzy pairwise comparisons of each $i-j$ criteria

Criteria	C1	C2	C3	C4	C5	C6	C7	C8
C1	[(0.50, 1.00, 1.50)]	[(2.00, 2.50, 3.00)]	[(1.75, 2.25, 2.75)]	[(1.67, 2.17, 2.67)]	[(1.33, 1.83, 2.33)]	[(1.50, 2.00, 2.50)]	[(0.33, 0.40, 0.51)]	[(1.75, 2.25, 2.75)]
C2	[(2.10, 2.60, 3.10)]	[(0.50, 1.00, 1.50)]	[(1.83, 2.33, 2.83)]	[(1.83, 2.33, 2.83)]	[(1.64, 2.14, 2.64)]	[(1.63, 2.13, 2.63)]	[(0.35, 0.42, 0.55)]	[(1.93, 2.43, 2.93)]
C3	[(1.88, 2.38, 2.88)]	[(1.88, 2.38, 2.88)]	[(0.50, 1.00, 1.50)]	[(1.40, 1.90, 2.40)]	[(1.20, 1.70, 2.20)]	[(1.63, 2.13, 2.63)]	[(0.37, 0.47, 0.64)]	[(1.67, 2.17, 2.67)]
C4	[(2.10, 2.60, 3.10)]	[(1.90, 2.40, 2.90)]	[(2.00, 2.50, 3.00)]	[(0.50, 1.00, 1.50)]	[(1.80, 2.30, 3.80)]	[(1.80, 2.30, 2.80)]	[(1.00, 1.50, 2.00)]	[(1.83, 2.33, 2.83)]
C5	[(1.70, 2.20, 3.70)]	[(1.50, 2.00, 2.50)]	[(1.67, 2.17, 2.67)]	[(1.83, 2.33, 2.83)]	[(0.50, 1.00, 1.50)]	[(1.60, 2.10, 2.60)]	[(0.35, 0.43, 0.56)]	[(1.90, 2.40, 2.90)]
C6	[(1.88, 2.38, 2.88)]	[(1.75, 2.25, 2.75)]	[(1.88, 2.38, 2.88)]	[(1.25, 1.75, 2.25)]	[(2.33, 2.83, 3.23)]	[(0.50, 1.00, 1.50)]	[(2.00, 2.50, 3.00)]	[(1.50, 2.00, 2.50)]
C7	[(2.14, 2.64, 3.14)]	[(2.00, 2.50, 3.00)]	[(1.88, 2.38, 2.88)]	[(2.25, 2.75, 3.25)]	[(2.00, 2.50, 3.00)]	[(1.93, 2.43, 2.93)]	[(0.50, 1.00, 1.50)]	[(2.25, 2.75, 3.25)]
C8	[(1.25, 1.75, 2.25)]	[(1.00, 1.50, 2.00)]	[(1.50, 2.00, 2.50)]	[(1.50, 2.00, 2.50)]	[(1.50, 2.00, 2.50)]	[(2.00, 2.50, 3.00)]	[(2.00, 2.50, 3.00)]	[(0.50, 1.00, 1.50)]

Evaluation of Alternatives with MAUT for Final Ranking

This study compared 12 alternative urban transportation scenarios for the eight selected indicators to decide the most sustainable transportation scenario, which considered the transport modes used. These 12 urban transport scenarios were selected from the applied transport scenarios for a city with a population of 1,434,357, and the characteristics of the alternatives are given in Table 7.

Kayseri, Central Anatolian Region, Türkiye covers 16,917 km². Kayseri's urban population is approximately half of its rural population, and the city has experienced rapid urbanization relative to the rest of Türkiye. In Kayseri, migration from the countryside to the city is strongly influenced by expanding industries (ORAN 2018). In addition, the urban part of the city has a flat and uneven topography, which helps urban transportation. It has a very advantageous geological structure that is particularly well suited for rail

and bicycles as forms of urban mobility due to its accessibility. Therefore, the primary modes of transportation in Kayseri are the tramway, bus, and bicycle.

Nonmotorized transportation (e.g., walking and cycling) were less expensive, more environmentally friendly, and relatively fast for distances of ≤ 5 km compared with motorized transport modes. To provide efficient and comfortable passenger transit within urban areas, motorized transportation, such as buses, cars, and railway vehicles, were required to travel longer distances (Advani et al. 2021). This study classified urban transportation alternatives into three categories (e.g., low, medium, and high-motorized), which depended on the number of motorized and non-MVs as given in Table 7. As the number of bus and tramway vehicles increased, the motorization level of the alternatives increased. The degree to which alternatives were motorized grew parallel with the increasing number of buses and tramways.

The steps in the MAUT methods for the evaluation of alternatives were (Ozari and Kurtulmuş 2017).

1. Create the decision matrix and determine the criteria and alternatives, as given in Table 8.
2. Calculate the weight for each criterion. The sum of each weight (w_i) value must be equal to

$$\sum_{i=1}^m w_i = 1$$

3. Create the normalized decision matrix, as given in Table 9.

Table 6. M_i and N_i weights of criteria

Criteria	M_i	N_i
C1	0.425	0.133
C2	0.388	0.121
C3	0.377	0.118
C4	0.410	0.128
C5	0.385	0.120
C6	0.370	0.115
C7	0.505	0.158
C8	0.344	0.107

Table 7. Characteristics of sustainable transportation alternatives

Classification	Alternatives	Number of vehicles		
		Tramway	Bus	Bicycle
High-motorized	A1	High (>40)	High (>700)	Low (<600)
	A2	High (>40)	Medium (600–700)	Low (<600)
	A3	High (>40)	High (>700)	High (>600)
	A4	High (>40)	Medium (600–700)	High (>600)
Medium-motorized	A5	Low (<40)	Medium (600–700)	Low (<600)
	A6	Low (<40)	High (>700)	High (>600)
	A7	High (>40)	Low (<600)	Low (<600)
	A8	Low (<40)	High (>700)	Low (<600)
Low-motorized	A9	Low (<40)	Medium (600–700)	High (>600)
	A10	High (>40)	Low (<600)	High (>600)
	A11	Low (<40)	Low (<600)	Low (<600)
	A12	Low (<40)	Low (<600)	High (>600)

Table 8. Decision matrix for alternatives

Alternatives	Environmental			Economic			Social	
	C1 tCO ₂ e	C2 MWh	C3 L	C4 %	C5 %	C6 %	C7 Number	C8 Number
A1	23,424	46,218	3,807,348	94	4	2	10	6.02
A2	22,821	24,895	3,601,906	95	3	2	9	5.53
A3	24,028	26,019	3,618,101	97	1	2	8	6.02
A4	23,424	49,877	3,807,348	96	2	2	9	6.02
A5	23,233	34,833	3,431,012	94	3	3	7	4.92
A6	23,233	38,624	3,807,668	94	4	2	10	5.96
A7	23,423	46,194	3,068,904	96	2	2	7	4.86
A8	23,233	34,846	3,807,668	96	2	2	10	5.81
A9	23,233	39,189	3,431,012	97	3	1	9	5.83
A10	23,423	49,852	3,068,904	95	3	2	7	5.75
A11	23,232	18,537	3,327,196	97	2	1	6	4.83
A12	23,232	38,600	3,327,196	95	2	3	4	4.83

4. Calculate the utility values

$$\text{For criteria to be maximized: } ui(x_i) = \frac{x - x_i^-}{x_i^+ - x_i^-} \quad (19)$$

$$\text{For criteria to be minimized: } ui(x_i) = \frac{x_i^+ - x}{x_i^+ - x_i^-} \quad (20)$$

where x_i^- = worst value of the alternatives; and x_i^+ = best value of the alternatives.

Table 9. Normalized decision matrix

Alternatives	Environmental			Economic			Social	
	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.50	0.12	0.00	1.00	0.00	0.50	0.00	0.00
A2	1.00	0.80	0.28	0.67	0.33	0.50	0.17	0.41
A3	0.00	0.76	0.26	0.00	1.00	0.50	0.33	0.00
A4	0.50	0.00	0.00	0.33	0.67	0.50	0.17	0.00
A5	0.66	0.48	0.51	1.00	0.33	0.00	0.50	0.92
A6	0.66	0.36	0.00	1.00	0.00	0.50	0.00	0.05
A7	0.50	0.12	1.00	0.33	0.67	0.50	0.50	0.97
A8	0.66	0.48	0.00	0.33	0.67	0.50	0.00	0.18
A9	0.66	0.34	0.51	0.00	0.33	1.00	0.17	0.16
A10	0.50	0.00	1.00	0.67	0.33	0.50	0.83	0.23
A11	0.66	1.00	0.65	0.00	0.67	1.00	0.67	1.00
A12	0.66	0.36	0.65	0.67	0.67	0.00	1.00	1.00

5. Calculate total utility (U_i), as given in Table 10.

$$U_i = \sum_{j=1}^m w_j U_{ij} \text{ for all } i \quad (21)$$

6. Rank the alternatives for the total utility values. Higher utility values corresponded to better alternatives.

The collected data for each alternative under three criteria categories are given in Table 8 as a decision matrix.

The normalized utility values were calculated with Eqs. (19) and (20), which assigned one for the best value and zero for the worst value for each criterion, as given in Table 9.

Finally, a utility matrix was obtained with the use of Eq. (21), and the sum of each criterion value gave the total utility value of each alternative, as given in Table 10

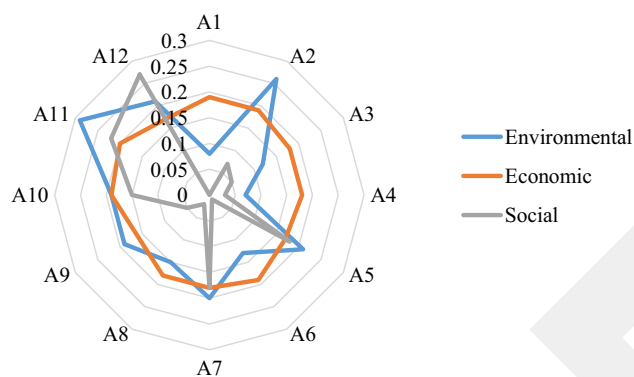
$$U_1 = \sum_{j=1}^8 w_j U_{1j} = 0.27 \text{ for Alternative 1}$$

The MAUT analyses were conducted with similar calculations for the other alternatives, and the results are summarized in Table 10. The ranking of the alternatives in descending order was 11, 12, 7, 5, 10, 2, 9, 3, 8, 6, 4, and 1, which depended on the total utility values. In addition, Fig. 2 shows the results of the total utility values for each alternative by a radar chart to illustrate the performance of the transportation alternatives from the environmental, economic, and social aspects.

From an environmental perspective, Alternative A11 had the best performance with 0.29 of the environmental total utility

Table 10. Utility matrix and results

Alternatives	Environmental			Economic			Social		Sum
	C1	C2	C3	C4	C5	C6	C7	C8	
A1	0.07	0.01	0.00	0.13	0.00	0.06	0.00	0.00	0.27
A2	0.13	0.10	0.03	0.09	0.04	0.06	0.03	0.04	0.52
A3	0.00	0.09	0.03	0.00	0.12	0.06	0.05	0.00	0.35
A4	0.07	0.00	0.00	0.04	0.08	0.06	0.03	0.00	0.27
A5	0.09	0.06	0.06	0.13	0.04	0.00	0.08	0.10	0.55
A6	0.09	0.04	0.00	0.13	0.00	0.06	0.00	0.01	0.32
A7	0.07	0.01	0.12	0.04	0.08	0.06	0.08	0.10	0.56
A8	0.09	0.06	0.00	0.04	0.08	0.06	0.00	0.02	0.34
A9	0.09	0.04	0.06	0.00	0.04	0.12	0.03	0.02	0.39
A10	0.07	0.00	0.12	0.09	0.04	0.06	0.13	0.02	0.52
A11	0.09	0.12	0.08	0.00	0.08	0.12	0.11	0.11	0.69
A12	0.09	0.04	0.08	0.09	0.08	0.00	0.16	0.11	0.64

**Fig. 2.** Comparison of the urban transportation alternatives from environmental, economic, and social aspects.

value, as shown in Fig. 2, which was due to the lowest energy consumption and lower depletion of nonrenewable resources at 18,537 MWh and 3,327,196 L, respectively (Table 8). In addition, Alternative A1 had the worst performance due to the highest consumption (3,807,348 L) of non-renewable resources compared with the others (Table 8). Therefore, high-motorized transportation alternatives showed a low performance from the environmental perspective; and a significant number of motor vehicles affected the environmental impacts of an urban transportation system negatively.

From an economic perspective, Alternative A11 presented the best performance (0.2 of the economic total utility value), because of the lowest percentage of fuel costs and lower operational costs at 1% and 2%, respectively (Table 8). In addition, it had a low number of tramway vehicles (<600), an environmentally friendly transport mode compared with the bus; however, it caused higher maintenance costs due to periodic maintenance and repair requirements. In addition, A9 had the worst performance from an economic perspective due to the highest percentage of the operational cost compared with the other alternatives.

From a social perspective, Alternative 12 showed the highest performance for the lowest number of motor vehicles for public transport per 10,000 population (C8) and the lowest number of fatalities or injuries (C7), with 4.83 and four, respectively (Table 8). Safety is one of the main criteria to evaluate transportation systems from a social perspective. Therefore, fewer fatalities and injuries indicated that the system was safer and vice versa. However, Alternatives A1, 6, and 8 had the highest fatalities or injuries, with 10. Therefore, it was the worst case among the other alternatives

from a social perspective. The results showed that low-motorized urban transportation alternatives were more sustainable than motorized and high-motorized alternatives from social perspectives.

According to the overall results, Alternative 11 was the best, and Alternative 12 was the second best alternative with the holistic perspective of sustainability that considered environmental, economic, and social aspects. Alternatives A11 and 12 were low-motorized urban transportation alternatives with a low number of bus and tramway vehicles, which was the primary transport mode for the source of electricity consumption in an urban transportation system. The results indicated that low-motorized urban transportation alternatives were more sustainable than motorized and high-motorized alternatives. Intermodal, multimodal transport, and mode shift approaches enhanced sustainability (Van Fan et al. 2018). In addition, DMs should holistically evaluate the urban transport systems when achieving more sustainable transport systems. This should cover people, the planet, and profit. More sustainable transportation systems would be achieved if all aspects were adequately optimized.

Finally, the criteria weights were calculated with the HF-AHP method, which was a more sophisticated method that was developed from conventional AHP (Sirisawat and Kiatcharoenpol 2018). Fuzzy AHP (F-AHP) is an extension of Saaty's theory (Saaty 1980), which provides a better description for most of the decision-making problems compared with conventional AHP (Askin and Ozdagoglu 2007). Then, the weights that were obtained from F-AHP and conventional AHP were used in the MAUT to select the most sustainable transportation alternative among the 12 urban transportation alternatives. In addition, the results from the HF-AHP and MAUT methods were compared, as given in Table 11.

The ranks of the alternatives were similar to the three integrated methods; however, some differences were seen due to distinction when the weights were calculated. According to the results, A11 was the best alternative in HF-AHP, but A12 was the best alternative in the integrated F-AHP method and the conventional AHP that was integrated with the MAUT method.

The consistency ratio (CR) was calculated [$CR = CI/RI(n)$] to assess the consistency of pairwise comparisons where the consistency index (CI) was given by $CI = ((\lambda_{max} - n)/(n - 1))$, where the random consistency index was $RI(n)$ for matrixes of order n and the principal eigenvalue of the judgment matrix was λ_{max} . The CR threshold was 0.10 in this study. If CR was <0.10, the pairwise

Table 11. Comparison of results from MAUT with HF-AHP, F-AHP, and AHP

Alternatives	HF-AHP and MAUT		F-AHP and MAUT		AHP and MAUT	
	Total utility value	Rank	Total utility value	Rank	Total utility value	Rank
A1	0.27	12	0.26	11	0.23	11
A2	0.52	6	0.46	6	0.45	6
A3	0.35	8	0.36	7	0.35	7
A4	0.27	11	0.26	12	0.24	12
A5	0.55	4	0.54	4	0.53	5
A6	0.32	10	0.30	9	0.28	9
A7	0.56	3	0.53	5	0.56	4
A8	0.34	9	0.29	10	0.27	10
A9	0.39	7	0.35	8	0.33	8
A10	0.52	5	0.58	3	0.58	3
A11	0.69	1	0.66	2	0.68	2
A12	0.64	2	0.67	1	0.70	1

Table 12. Results of sensitivity analysis for F–AHP with MAUT method

Sensitivity analysis	Alternatives/F–AHP with MAUT rank											
	1	2	3	4	5	6	7	8	9	10	11	12
	11	6	7	12	4	9	5	10	8	3	2	1
# of first rank	0	0	0	0	0	0	0	0	0	0	12	16
# of second rank	0	2	0	0	1	0	1	0	0	0	16	8
# of third rank	0	0	0	0	3	0	3	0	0	20	0	2
# of fourth rank	0	1	0	0	15	0	7	0	0	4	0	1
# of fifth rank	0	3	0	0	8	0	16	0	1	0	0	0
# of sixth rank	0	21	0	0	0	0	1	0	2	3	0	1
# of seventh rank	0	0	18	0	1	1	0	0	7	1	0	0
# of eighth rank	0	1	5	0	0	3	0	3	16	0	0	0
# of ninth rank	0	0	2	0	0	16	0	9	1	0	0	0
# of tenth rank	1	0	2	3	0	5	0	16	1	0	0	0
# of eleventh rank	7	0	0	18	0	3	0	0	0	0	0	0
# of twelfth rank	20	0	1	7	0	0	0	0	0	0	0	0
Average rank	11.68	5.75	7.71	11.14	3.96	9.21	4.46	9.46	7.61	3.61	1.57	1.71

Table 13. Results of sensitivity analysis for proposed method (HF–AHP with MAUT)

Sensitivity analysis	Alternatives/Proposed method rank											
	1	2	3	4	5	6	7	8	9	10	11	12
	12	6	8	11	4	10	3	9	7	5	1	2
# of 1st rank	0	0	0	0	0	0	0	0	0	0	28	0
# of 2nd rank	0	0	0	0	0	0	0	0	0	0	0	28
# of 3rd rank	0	0	0	0	4	0	24	0	0	0	0	0
# of 4th rank	0	0	0	0	24	0	4	0	0	0	0	0
# of 5th rank	0	9	0	0	0	0	0	0	0	19	0	0
# of 6th rank	0	19	0	0	0	0	0	0	0	9	0	0
# of 7th rank	0	0	0	0	0	0	0	0	28	0	0	0
# of 8th rank	0	0	24	0	0	0	0	4	0	0	0	0
# of 9th rank	0	0	3	0	0	1	0	24	0	0	0	0
# of 10th rank	0	0	1	0	0	27	0	0	0	0	0	0
# of 11th rank	4	0	0	24	0	0	0	0	0	0	0	0
# of 12th rank	24	0	0	4	0	0	0	0	0	0	0	0
Average rank	11.86	5.68	8.18	11.14	3.86	9.96	3.14	8.86	7.00	5.32	1.00	2.00

comparison matrix had an acceptable consistency, and the weights were valid for the applications (Kordi and Brandt 2012; Ananda and Herath 2008). In this study, the pair comparisons were consistent with the overall mean CR for eight criteria of <0.007.

Sensitivity Analysis

This section presents the sensitivity analyses on the weights of the criteria to reveal the influence that the weights had on the rankings that were obtained for several scenarios to determine the robustness of the results. The sensitivity analysis examined how alternative selection changed as the relative importance of the criteria changed. The analyses were performed to exchange each criterion weight for the F–AHP with the MAUT methods and the proposed method; the results of the experiments are given in Tables 12 and 13. This showed how many times each alternative took place, which rank was obtained in all the experiments, and the average of the ranks that were obtained from 28 experiments for the F–AHP with MAUT methods and the proposed method.

As given in Table 12, Alternative 12, ranked as the best alternative in the F–AHP with MAUT methods, scored 16 to be ranked first among the 28 experiments. As listed in Table 13, Alternative 11, which was suggested as the most sustainable urban transportation scenario in the proposed method, scored 28 in 28 experiments. In addition, 1,2 and 7 ranks have exact results of average ranks in sensitivity analysis and the other ranks have similar results in

proposed method. The proposed methodology was found to be robust and sensitive to the criterion weights in the sensitivity analysis.

This study presented an innovative and comprehensive methodology when determining the feasibility of sustainable urban transportation projects and renovating existing urban transportation networks. The methodology offered DMs a holistic approach to urban transportation planning that considered environmental, economic, and social factors. In addition, the findings were addressed with the urban transportation industry, which agreed with the concept after the sensitivity analysis was considered.

Conclusion

This study could encourage DMs, planners, and professionals in the urban transportation industry to use this methodological framework of sustainable urban passenger transportation to make design and planning decisions for urban transportation projects. The proposed methodology was based on HF–AHP and MAUT and were implemented for the first time for urban transportation alternatives in Kayseri, Türkiye, to decide the most sustainable alternative. The weights of the sustainable indicators were calculated with HF–AHP, and the final ranking of the alternatives was obtained with the MAUT method. In total, 12 urban transportation alternatives were evaluated for eight sustainable transportation indicators that were grouped into three categories: (1) environmental; (2) economic; and (3) social for comprehensive decision analysis. The

obtained HF–AHP results revealed that environmental and social criteria are the most and least significant categories of criteria, with weights of 0.372 and 0.265, respectively. Therefore, the environmental criteria had the highest impact on the selection of the most sustainable alternative compared with the economic and social criteria. DMs must prioritise environmental criteria for the design, planning, and operation of urban transportation systems. In addition, the number of fatalities or injuries (C7) and motor vehicles for public transport per 10,000 population (C8) were the most and least significant subcriteria with weights of 0.158 and 0.107, respectively. Alternative 11, which was under the low-motorized urban transportation category, had the best alternative for sustainability performance from a holistic perspective that considered the environmental, economic, and social aspects. In addition, A11 was the most sustainable alternative from the environmental and economic perspectives, and A12 was the most sustainable from a social perspective from the 12 urban transportation alternatives. The results revealed that low-motorized urban transportation alternatives showed higher sustainable performance than the motorized and high-motorized alternatives. The sensitivity analysis was performed to confirm the robustness of the methodology. The sensitivity analysis results revealed that the proposed method was robust and effective when determining sustainable urban transportation scenarios.

The AHP and MAUT methods have been used in some areas due to their easy application; however, to the best of the authors' knowledge, no study exists in the literature on integrated HF–AHP and MAUT for sustainable transportation. This study could contribute to fill this research gap by providing a new integrated methodology (HF–AHP and MAUT) in sustainable transportation that considered a triple bottom approach. The main advantage of HFSs was to obtain more reasonable decision results due to the hesitancy of the preferences of DMs. The proposed method could be applied to different real-world problems in various areas, such as the industrial, health, and transportation sectors. Additional indicators, such as land usage and noise, could be applied for a more comprehensive sustainability evaluation and could be used in future research. In addition, in further studies from the multiobjective perspective, the tradeoff between total transportation cost and environmental satisfaction objectives could be investigated.

Data Availability Statement

Some or all data, models, or codes used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the "Acknowledgments" section. The inventory data that Kayseri Transportation provided is confidential. Requests for the underlying data may be made via the corresponding author.

Acknowledgments

The authors would like to thank and acknowledge Kayseri Transportation for providing the necessary inventory data for this research.

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