



Mode ranking underpinning an urban mobility analysis: Urban mobility quality index case study

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ABSTRACT

Background: This article proposes a model for evaluating the quality of public transportation modes. **Methods:** The Fuzzy-SAW method was used, combining fuzzy logic with the Simple Additive Weighting (SAW) technique. Applied to the city of Rio de Janeiro, the case study uses data from the Urban Mobility Quality Index (IQMU) collected in four rounds of research. The methodology translates users' subjective perceptions into objective indicators, allowing the ranking of transportation modes (metro, train, ferry, and bus) based on perceived quality. **Finding:** Safety and fare were the most influential criteria, with the metro emerging as the best-rated mode. The study emphasizes the relevance of multicriteria methods for complex decision-making in urban mobility. **Conclusion:** The application of the Fuzzy-SAW modeling method to complex decision-making contexts involving multiple variables and subjective criteria proved essential in providing a systematic framework for evaluating and selecting alternatives, supporting more rational, transparent, and justifiable decisions. In summary, by quantifying subjective perceptions, this study contributes to a better understanding of public transportation from the user's perspective, potentially impacting public policies on urban mobility regarding resource prioritization oriented towards use, responsiveness to user needs, and allowing for the evaluation of the effectiveness of these resources. This is a key factor for the development of more resilient, humanized, and sustainable cities, where mobility is a right accessible to all citizens. **Novelty/Originality of this article:** Using the hybrid Fuzzy-SAW method, it is possible to handle subjective and sparse multicriteria elements, expanding the capacity for criteria representation, as well as the accuracy of records in real representations.

KEYWORDS: Fuzzy-SAW; Rio de Janeiro; urban mobility.

1. Introduction

When conducted in a planned and sustainable manner, urban planning can drive significant advances in the economic, social, and environmental progress of cities, enhancing the present and future quality of life. In this context, urban management plays an essential role in organising urban space and articulating different modes of transportation, promoting mobility as a right, rather than a privilege. The absence of systemic planning undermines accessibility and efficient land use, directly affecting social integration and the efficiency of public and non-motorised modes of transportation.

Urban mobility is intrinsically linked to urban development and socio-spatial justice. When neglected, it results in severe negative impacts, including inequality, loss of income, and widespread environmental degradation. Public transportation networks are fundamental for structuring urban mobility, with their quality directly affecting user

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perceptions. Factors such as punctuality, comfort, safety, and modal integration underpin trust and regular use of collective transportation facilities. In contrast, instability in these services fuels migration to individual transportation options, thus ratcheting up urban challenges.

In order to ensure good quality transportation services, urban mobility management must consider citizen standpoints and sustainability principles. Rutka et al. (2024) stress that effective mobility planning is one of the main challenges faced by large cities, especially when heavy traffic pumps up greenhouse gas emissions. For Müller-Eie & Kosmidis (2023), improving urban mobility is essential for building greener, more efficient, and socially equitable cities. Furthermore, Chatziioannou et al. (2023) emphasise that proper management of transportation activities is fundamental for sustainable development, with urban mobility indicators (particularly when focused on sustainability) being key tools for measuring and assessing potential solutions. Medina-Molina et al. (2024) stress that these indicators underpin a better understanding of complex urban phenomena and the formulation of responses to social impacts. However, they also warn that analytical approaches are needed that are sensitive to the complexity of this issue, due to difficulties related to data heterogeneity and subjectivity. Finally, Yildirim et al. (2022) argue that indicators are essential for identifying strengths and weaknesses in urban mobility, thus guiding interventions pursuing improvements. It is noted that indicator-based studies focused on urban mobility, accessibility and sustainable transportation are not rare. Examples include input sources disseminated through several studies based on the following publications: UN-HABITAT (2015), UITP (2019), UN-ESCAP (2019), Pupprecht (2020), ADB (2022), UITP (2022), WK (2022), Berkeley (2023) and FHB (2025).

In the Brazilian context, several approaches have been deployed to measure urban mobility, mainly through indices and indicators drawn from data surveys. Notable among them is the Sustainable Urban Mobility Index (IMUS – Índice de Mobilidade Urbana Sustentável) developed by Costa (2008), which supports urban planning based on the economic, environmental, and social dimensions of sustainability. With nine themed domains, this Index uses a scale of 0 to 1.0, where higher values indicate better performances. This Index was used recently by Leitão et al. (2024) and Bonifácio et al. (2023), with values varying from 0.375 in Campo Mourão to 0.787 in Curitiba, for example, and was also updated by Amaral et al. (2025).

Another relevant contribution is the Urban Mobility Quality Index (IQMU – Índice da Qualidade da Mobilidade Urbana) proposed by Sucena & Cury (2022; 2023). This Index evaluates multiple modes of urban transportation – such as walking, cycling, cars, motorcycles, taxis, and public transportation – through partial indicators. For public transportation, it analyses attributes such as fares, comfort, and accessibility. Based on mathematical modelling using artificial intelligence, and with higher values (on a scale of 0 to 10) reflecting better perceptions of urban mobility quality, round 5 of the IQMU presented the following findings: 4.6 for Rio de Janeiro; 5.4 for São Paulo; and 4.8 for Belo Horizonte.

Urban mobility upgrades require precise diagnoses of current conditions, identifying trends and steering actions. Continuous monitoring is essential for interpreting and quantifying the multiple dimensions of mobility, especially those related to public transportation. This provides core input that is crucial for urban planning. Along these lines, Deming (1990) underscores the importance of measuring and understanding, in pursuit of better management, synthesising this principle in the statement: "You cannot manage what you do not measure."

Rodrigues (2006) emphasises that recurrent user perceptions are vital for establishing quality standards in public transportation. Fonseca & Borges (2002) expand this view by identifying three factors that influence user satisfaction: perceived quality, perceived value (price) and expectations. These authors also stress that user satisfaction surveys are basic regulation and inspection tools, keeping management aligned with social demands, rather than just the technical views of administrators. Esperidião et al. (2005) add that the

satisfaction surveys should also assess service expectations and perceptions, as elements shaping user experiences.

Consequently, this paper proposes a multicriteria approach to modal assessment using the Fuzzy Simple Additive Weighting (Fuzzy-SAW) method that can transform subjective perceptions of public transportation into objective, measurable, and traceable values over time. This modelling tool was used in the City of Rio de Janeiro, based on data from rounds 2 to 5 of the Urban Mobility Quality Index (IQMU). These Rounds were selected because they reflect relevant variations in user behaviours, particularly with regard to the effects of the pandemic, with the first three using online data collection techniques, and the final round working with in-person research.

Regarding the use of the Fuzzy-SAW method, among the most recent studies - between 2022 and 2026 - that address the topic "Sustainable Urban Mobility Index," the use of parametric techniques for few input variables or a hybrid structure with multicriteria, for a larger volume of initial data, is predominant. Fuzzy Theory, in its various lines of research, is also used, including with multicriteria models. As a parametric example, it is possible to highlight the model with only six input variables by Zotov & Tsenzharik (2025) to assess the quality of mobility; and that of Liponhay et al. (2023), which creates a dynamic mobility index from data collected from vehicles with GPS. For multicriteria models, pure or hybrid applications with AHP - Analytic Hierarchy Process stand out, with emphasis on Villegas-Flores et al. (2026), Lu et al. (2022), Oliveira & Feroni (2022) and Canal et al. (2023). The latter two studies are based on the Costa model (2008), widely used in Brazil, as noted by Souza & Castañón (2024).

Aiming to reduce the implicit uncertainties when capturing human perceptions, Fuzzy Theory is used with some versatility, due to the vast dissemination of approaches developed since the early days of Zadeh (1965). As a representative of this theoretical line, Kilic & Demirel (2025) stand out, presenting a study with an overview of existing research on fuzzy decision systems applied to sustainable public transport with multi-criteria structures, including AHP and SAW. This last method is rarer, although it is evaluated as an applicable alternative in numerous studies for multiple alternatives and criteria.

2. Methods

According to the methodological classification proposed by Prodanov & Freitas (2013), this research project has both qualitative and quantitative characteristics. It resembles qualitative analyses by examining relationships between urban mobility and user perceptions, while moving into the quantitative field by translating these perceptions into numerical values through mathematical modelling based on Fuzzy Theory. The purpose of this applied research project is to build models (mod-IQMU and mod-QUALI) able to rank the types of public transportation available in the City of Rio de Janeiro, based on real data. From an objective standpoint, this research project blends exploratory and explanatory aspects. Its exploratory approach is reflected in the development and testing of the mod-QUALI model, which ranks modes of transportation. Its explanatory nature stems from the causal analysis comparing collected data and observed results, underpinning a better understanding of how different attributes influence perceptions of transportation service quality.

On the technical side, the methodology is split into two main stages. The first is related to the mod-IQMU, with data collected in four rounds, based on samples of the population of Rio de Janeiro. These data are obtained through structured questionnaires with a five-point Likert scale (Vonglao, 2017) that captures user perceptions after their trips (ex-post-facto collection). These responses are fuzzified by using Fuzzy-Integrals (Tanaka, 1997) and trapezoidal fuzzy numbers - adapted from Kumar & Dhiman (2021) and Piasecki & Łyczkowska-Hanćkowiak (2021) -, mapping qualitative criteria within a quantitative structure. Data from different rounds are then aggregated through fuzzy number algebra, as recommended by Prokopowicz et al. (2017) and Dubois & Prade (1985), allowing these

perceptions to be consolidated into a single decision matrix using the PERT method, following the guidance of Shaw et al. (1999).

Next comes the mod-QUALI stage, where alternatives are determined (modes analysed: subway, urban train, ferry, and urban bus) and perceived quality criteria are selected, based on exploratory research. The criteria weights are obtained in the second round, also using a Likert scale and linguistic label fuzzification, followed by a defuzzification process for use by the Fuzzy-SAW Utility Function (Abadi et al., 2019 and Vaz et al., 2017). This function combines the decision matrix weights and normalised values, allowing a numerical value to be obtained in the \mathbb{R} domain for each mode of transportation, after which they can be ranked, based on user perceptions.

2.1 Fuzzy theory

Initially mentioned by Zadeh (1965), Fuzzy Theory opened up possibilities of representing real-world conditions or situations with subjectivities, linearities and non-linearities, where definitions have no clear boundaries. Ross (1999) points out that, for an element in a universe containing fuzzy sets such as those observed by Zadeh, the transition may be transcribed as a subjective boundary, where it exists between belonging and non-belonging to a given set. In this sense, taking a Fuzzy Set A as a list of elements in a certain universe of the $X = \{x_1, x_2, \dots, x_i\}$ discourse – or a subset of X – with the respective $\mu_A(x_i)$, levels of pertinence, forming $(x_i, \mu_A(x_i)) : X \in A$ ordered pairs that are mapped through the $\mu_A : A \rightarrow [0,1]$ pertinence functions. The higher the $\mu_A(x_i)$ value, the better the A characteristic property is satisfied. These elements may be represented in a discrete (Eq. 1) or continuous (Eq. 2) manner, known as Integral-Fuzzy (Tanaka, 1997).

$$A = \mu_A(x_1)/X_1 + \mu_A(x_2)/X_2 + \dots + \sum_{i=1}^n \mu_A(x_i) / X_i \tag{Eq. 1}$$

$$A = \int_x \mu_A(x_i) / X_i \tag{Eq. 2}$$

A crisp variable in the \mathbb{R} domain must be fuzzified for assessment in the fuzzy domain, meaning it has to be represented by a linguistic variable that is the name of the fuzzy set. The latter can be represented by linguistic labels - or linguistic terms - that are based on their pertinence functions, which may be represented by Fuzzy-Integrals (Eq. 2). Shaw et al. (1999) highlight that these linguistic terms may be based on analysts' experiences and the type of processes to be controlled. They also mention that the number of functions should vary between 2 and 7 in actual practice, using common sense to weigh the greatest accuracy for the outcomes against the most appropriate computational demands. The five-element Likert scale is an adequate method for the median approach. It is supported by the Vonglao (2017) approach, which notes that the traditional Likert scale (Likert, 1932) can be improved by applying four steps for processing Fuzzy variables – Fuzzification, Processing, Aggregation, and Defuzzification – which are commonly used in Fuzzy Logic by the Mamdani approach.

In fuzzy set theory, uncertainty and vagueness are modeled through mathematical representations that extend classical set concepts. A certain fuzzy subset Y of A may be represented as a fuzzy number, which has the crisp subset in the universe X as the domain of a certain pertinence function, representing a linguistic term. This representation allows qualitative judgments to be translated into quantitative forms for analytical purposes. This subset may be expressed as normal if there is a y_k in R, whereby $\mu_Y(y_k) = 1$. The fuzzy number is used to represent situations in which the data are not precise, the most common being those related to triangular and trapezoidal functions (Fig. 1). Therefore, fuzzy numbers provide a flexible framework for handling imprecision in real-world decision-making problems.

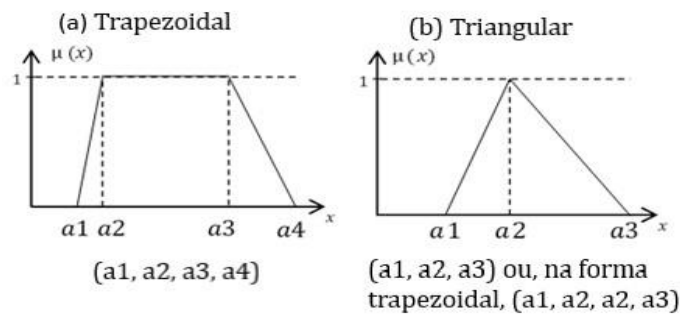


Fig. 1. The fuzzy number (a) trapezoidal and (b) triangular fuzzy numbers

Taking two fuzzy numbers in trapezoidal form (Fig. 1a), $A'1=(a11, a12, a13, a14)$ and $A'2=(a21, a22, a23, a24)$, they may be used to structure fuzzy interval arithmetic. This formulation enables systematic mathematical operations to be performed under conditions of uncertainty and imprecision. As highlighted between (Eq. 3) and (Eq. 8), adapted from Kumar & Dhiman (2021) and Piasecki & Łyczkowska-Hanćkowiak (2021), these operations reflect interactions between fuzzy numbers, including addition, subtraction, product, division, scalar product, and scalar division.

$$\text{Addition: } A'1 \oplus A'2 = \{a11+a21, a12+a22, a13+a23, a14+a24\} \tag{Eq. 3}$$

$$\text{Subtraction: } A'1 \ominus A'2 = \{a11-a24, a12-a23, a13-a22, a14-a21\} \tag{Eq. 4}$$

$$\text{Product: } A'1 \otimes A'2 = \{a11.a21, a12.a22, a13.a23, a14.a24\} \tag{Eq. 5}$$

$$\text{Division: } A'1 \oslash A'2 = \{a11/a24, a12/a23, a13/a22, a14/a21\} \tag{Eq. 6}$$

$$\text{Scalar product } n: n.A'1 = \{n.a11, n.a12, n.a13, n.a14\} \tag{Eq. 7}$$

$$\text{Scalar division } n: A'1/n = \{a11/n, a12/n, a13/n, a14/n\} \tag{Eq. 8}$$

After processing the data in the fuzzy environment, it is necessary to return to the crisp domain, meaning real numbers. To do so, it is necessary to defuzzify the result represented by a fuzzy number that, according to Shaw et al. (1999), depends on the choice of the method in the context of the decision. This is because there are many options, including one based on the PERT distribution (a subset of the BETA distribution) that increases the weighting in the intermediate values, where the degree of pertinence is equal to 1, meaning that they are more likely to belong to the fuzzy set. In (Eq. 9), the output is recorded in the crisp domain represented by $Output_k$ in the PERT method, with an example being a certain trapezoidal fuzzy number $K = (a_1, a_2, a_3, a_4)$.

$$Output_k = \frac{a_1 + 2a_2 + 2a_3 + a_4}{6} \tag{Eq. 9}$$

2.2 Fuzzy-SAW

A decision-making process may be supported by methods, techniques and procedures designed to enhance the effectiveness of its responses, especially in problems where the cognitive capacity of the decision-maker is affected by the presence of several alternatives and multiple criteria, increased by the presence of vague and/or imprecise values. The Simple Additive Weighting (SAW) method ranks high among the best-known and approved multicriteria hierarchical methods favoured by the American school, due to its simplicity and the alignment between its results and more sophisticated techniques (Stanković et al., 2020; Piasecki et al., 2019; Zhu & Buchmann, 2002; Oliveira, 2018). As shown, this method consists of defining values for relationships between alternatives and criteria through a

decision matrix by assigning weights to the criteria, which results in a tiered list of the most appropriate alternatives (Abadi et al., 2019 and Vaz et al., 2017). The values related to each alternative are obtained by the Utility Function (Eq. 10):

$$S_i = \sum_{j=1}^n w_j \cdot r_{ij} \tag{Eq. 10}$$

In this context, S_i represents the utility function of the i th alternative, for $i=1,2,3,\dots,n$, while w_j denotes the weight of the j th criterion, with $j=1,2,3,\dots,n$, and r_{ij} corresponds to the normalized data of the i th alternative with respect to the j th criterion. Furthermore, in order to determine the criteria weights (w_j) based on the hierarchical ordering of their importance, a natural ranking approach is adopted, and consequently, the reciprocal form (Eq. 11) is applied. This approach ensures that higher-ranked criteria receive proportionally greater weights in the decision-making process.

$$w_j = \frac{\frac{1}{z_j}}{\sum_{k=1}^n \frac{1}{z_k}} \tag{Eq. 11}$$

In this context, z_j represents the importance of the j th criterion, with $j=1,2,3,\dots,n$. Furthermore, Fuzzy-SAW blends fuzzy theory precepts with the SAW method, allowing imprecise or subjective data reflecting alternatives and criteria to be processed in ways that are closer to the human mind (Amaral, 2016). The application of multicriteria SAW methods with fuzzy numbers enables the development of robust models in a simple manner, accommodating both linear and nonlinear variables that may be complex and imprecise. Thus, based on the simplification proposed by Lestari et al. (2020), the process adapted to the Fuzzy-SAW solution begins with determining the alternatives and criteria established for the problem, followed by developing the decision matrix that relates alternatives to criteria and populating it with standardized data, whether qualitative or quantitative. Subsequently, normalization is carried out, including the fuzzification of input data when necessary, after which the criteria weights are calculated according to their levels of importance in the decision-making process. Finally, the utility function is applied to generate a hierarchical ranking, where the highest value represents the most appropriate alternative.

2.3 Modelling

Following the five steps for the Fuzzy-SAW solution presented in the previous subitem results in a model that adequately represents the phenomenon under analysis. The first step for Fuzzy-SAW modelling refers to the definition of the alternatives and criteria established for the problem. The alternatives used in the mathematical model refer to modes of public transportation that, according to Macedo, da Silva and Costa (2008), include public bus, tram, light rail vehicle (VLT), ferry, urban train, and subway.

To define the attributes (criteria) for the modes of transportation, several previous studies were reviewed (Ferraz et al., 2020; Rezende & Aro, 2020; da Silva et al., 2020; da Costa & Pinheiro, 2019; Kureke et al., 2019a, 2019b; Tischer & Polette, 2019; Batista, 2018; Costa, 2018; Dos Santos et al., 2018; Ferreira et al., 2018; Guimarães et al., 2018; Lima & Carvalho, 2018; Moura, 2018; Pereira, 2018; Pinto & Galvão, 2018; Vasconcelos, 2009; NTU, 2008; Rodrigues & Serratini, 2008; Rodrigues, 2006; Sucena et al., 2006; Sucena et al., 2005). Based on these studies, the most frequently mentioned attributes include safety, cleanliness, comfort, accessibility, fluidity (related to time), conservation (maintenance), and user services.

Specifically, fare (C01) refers to the amount paid by the user for a trip, whether involving a single or multiple (intermodal) modes. In addition, cleaning (C02 for vehicles and C03 for facilities) is defined as the absence of debris that may interfere with the perception of cleanliness and the overall appearance of the environment. Furthermore, comfort (C04 for vehicles and C05 for facilities) relates to the absence of mental and/or physical tension and the presence of pleasant experiences, being influenced by factors such as noise, lighting, ventilation, smoothness of acceleration and deceleration, seat availability, protection from sun and rain, capacity and overcrowding, access dimensions, door width, and temperature.

Moreover, safety (C06 for vehicles and C07 for facilities) refers to the absence of accidents or risk factors, including user protection against violent acts in stations, terminals, stops, and vehicles. Similarly, accessibility (C08 for vehicles and C09 for facilities) concerns the ability to access, approach, use, and move within environments, including for people with special needs. In addition, fluidity (C10 for travel time and C11 for waiting time) represents the ease of transportation services, considering the relationship between travel time, origin-destination distance, and user perception. Likewise, conservation (C12 for vehicles and C13 for facilities) reflects the perceived maintenance conditions of vehicles and infrastructure. Finally, user services (C14) encompass empathic communication provided by personnel and supported by electronic systems at stations, terminals, stops, and within vehicles. The weights of these attributes are assessed through a hierarchy structured according to their importance to users, as presented in previous studies (Pavelski & Bernardinis, 2019; Estevam et al., 2019; Moreira, 2016; Lorenzetti, 2015; Rio Como Vamos & ITDP Brasil, 2015; Prefeitura de Ribeirão Preto, 2012). The outcome of this assessment results in the following hierarchy: 1 – fares and safety; 2 – fluidity (time/distance relationship); 3 – comfort; 4 – accessibility; 5 – cleanliness; 6 – conservation (maintenance); and 7 – user services, where a value of 1 indicates the highest level of importance.

3. Results and Discussion

The input data to be processed by the mod-IQMU and subsequently fed into the mod-QUALI consists of the records of IQMU data collection Rounds 2 to 5, conducted in April 2021, May 2021, August/September 2022, and April 2025, respectively. They form the IQMU by reflecting user perceptions of urban mobility performances. Their samples are dimensioned by calculating their size (Eq. 12) based on the 2022 Census, for the number of inhabitants in the City of Rio de Janeiro, generated by the Brazilian Institute for Geography and Statistics (IBGE).

$$n = \frac{NZ^2pq}{E^2(n-1) + Z^2pq} \quad (\text{Eq. 12})$$

Where n represents the sample size, N the population of the City of Rio de Janeiro, Z the confidence level, p the probability of success, q the probability of failure, and E the margin of error. The City of Rio de Janeiro has a population of 6.21 million inhabitants (IBGE, 2022). Based on Eq. (12), the calculated sample consisted of 385 respondents, considering a 5% margin of error, a 95% confidence level, and a 50% heterogeneous population distribution. In the second round, 498 responses were recorded, resulting in a 4.4% margin of error at a 95.0% confidence level. Subsequently, the third and fourth rounds each collected 452 responses, corresponding to a 4.6% margin of error with the same 95.0% confidence level. Finally, the last round included 791 responses, achieving a 3.5% margin of error at a 95.0% confidence level.

For this step, the Perceived Quality in the Mode of Transportation fuzzy variable is established, which may be identified as Very Bad, Bad, Fair, Good, and Excellent, following the five-score Likert structure. These linguistic labels are represented by their pertinence functions that map the discourse universe formed by real numbers (scores in the range

between 0 and 10) and levels of pertinence in the fuzzy view. The respective Fuzzy-Integrals (Eq. 2) run between (Eq. 13) and (Eq. 17).

$$Very\ Bad = \int_{0 \rightarrow 1}^{1 \rightarrow 0} -x + 1 / X \tag{Eq. 13}$$

$$Bad = \int_{0 \rightarrow 0}^{1 \rightarrow 1} x / X + \int_{1 \rightarrow 1}^{3 \rightarrow 1} 1 / X + \int_{3 \rightarrow 1}^{4 \rightarrow 0} -x + 4 / X \tag{Eq. 14}$$

$$Fair = \int_{3 \rightarrow 0}^{5 \rightarrow 1} \frac{x - 3}{2} / X + \int_{5 \rightarrow 1}^{7 \rightarrow 1} \frac{-x + 7}{2} / X \tag{Eq. 15}$$

$$Good = \int_{6 \rightarrow 0}^{7 \rightarrow 1} x - 6 / X + \int_{7 \rightarrow 1}^{9 \rightarrow 1} 1 / X + \int_{9 \rightarrow 1}^{10 \rightarrow 0} -x + 10 / X \tag{Eq. 16}$$

$$Excellent = \int_{9 \rightarrow 1}^{10 \rightarrow 1} x - 9 / X \tag{Eq. 17}$$

In order to perform the Utility Function (Eq. 10) calculations, it is necessary to transform the fuzzy integrals into trapezoidal fuzzy numbers, which relate alternatives to criteria. With four rounds, Eqs. (3) to (8) are used to aggregate these numbers, obtaining another equivalent representation of user perceptions. This aggregation is commonly used for the convergence of numbers/data in multi-criteria decision-making (Prokopowicz et al., 2017). The use of the arithmetic mean in the fuzzy context is considered a reinterpretation of the traditional format in the real-number domain (Dubois & Prade, 1985). Further details regarding fuzzy number aggregation and commonly used methods can be found in the literature (Prokopowicz et al., 2017; Merigó & Casanovas, 2010; Takács, 2010; Merigó & Casanovas, 2008; Dubois & Prade, 1985). Table 1 ahead presents the decision matrix with the fuzzy aggregation findings for each criterion, related to the alternatives. The criterion x alternative relationship is represented by a trapezoidal fuzzy number in the (a₁, a₂, a₃, a₄) format, as shown in Fig. 1.

Table 1. Decision matrix with the aggregation outcome (r_{ij})

Criteria	Alternatives (Modes of transportation)															
	Subway				Train				Barge				Bus			
C01	1.0	1.4	4.1	5.0	0.3	0.5	3.3	4.3	0.8	1.2	3.9	4.8	0.8	1.1	3.9	4.8
C02	3.1	4.3	6.3	7.1	1.6	2.2	4.7	5.6	2.5	3.5	5.6	6.5	1.3	1.8	4.4	5.3
C03	3.4	4.8	6.7	7.4	1.6	2.2	4.7	5.6	2.3	3.1	5.3	6.3	1.2	1.7	4.3	5.2
C04	2.7	3.8	5.9	6.7	1.5	2.0	4.5	5.5	3.3	4.6	6.5	7.3	1.6	2.2	4.7	5.6
C05	2.7	3.8	5.9	6.7	1.5	2.1	4.6	5.5	1.8	2.6	5.0	5.8	1.1	1.5	4.1	5.1
C06	3.8	5.6	7.3	7.8	2.1	2.9	5.2	6.1	4.1	6.1	7.8	8.1	1.6	2.2	4.7	5.6
C07	3.5	5.1	6.9	7.5	1.5	2.1	4.6	5.5	2.7	3.8	5.9	6.7	1.2	1.7	4.3	5.2
C08	3.0	4.2	6.2	7.0	1.8	2.6	5.0	5.8	2.6	3.7	5.9	6.6	2.1	2.9	5.2	6.1
C09	3.3	4.6	6.5	7.3	2.1	3.0	5.3	6.1	2.8	4.0	6.0	6.8	2.3	3.2	5.5	6.3
C10	2.5	3.5	5.7	6.5	0.8	1.0	3.8	4.8	1.8	2.5	4.9	5.8	1.2	1.7	4.3	5.2
C11	2.7	3.8	5.9	6.7	1.0	1.5	4.1	5.0	1.2	1.6	4.2	5.2	1.1	1.5	4.1	5.1
C12	2.4	3.2	5.4	6.4	0.7	1.0	3.7	4.7	1.7	2.2	4.7	5.7	0.8	1.1	3.8	4.8
C13	2.4	3.3	5.5	6.4	1.0	1.3	4.0	5.0	1.5	2.0	4.5	5.5	0.9	1.2	3.9	4.9
C14	3.5	4.9	6.8	7.5	2.8	4.0	6.0	6.8	3.1	4.3	6.3	7.1	2.8	3.9	6.0	6.8

The fourth step of the multicriteria method describes the need to calculate the criteria weights. A literature review in sub-item 4.1 defines their ranking by order of importance, as shown in Table 2. In confirmation, value 1 indicates the most important criterion – C01, C06, and C07 – in relation to the others, with these amounts reduced to an increasing extent.

Table 2. Criteria ranking by importance

Criteria	C01	C02	C03	C04	C05	C06	C07
Amounts	1	5	5	3	3	1	1
Criteria	C08	C09	C10	C11	C12	C13	C14
Amounts	4	4	2	2	6	6	7

The next step involves determining the weights for each criterion based on the selected method to ensure a balanced evaluation. This process allows the relative importance of each variable to be properly reflected in the analysis. The weights are calculated using (11), resulting in the normalised records shown in Table 3.

Table 3. Criteria weights (w_j)

Criteria	C01	C02	C03	C04	C05	C06	C07
Weights	0.165	0.033	0.033	0.055	0.055	0.165	0.165
Criteria	C08	C09	C10	C11	C12	C13	C14
Weights	0.041	0.041	0.083	0.083	0.028	0.028	0.024

The fifth and final step of the Fuzzy-SAW implementation consists of applying the utility function (Eq. 10) for ranking the alternatives. Here, the higher transportation mode quality is reflected in higher S_i . In order to determine the value representing each mode of transportation, based on the criteria and their weights, reflecting the convergence of user perceptions – it is necessary to apply (Eq. 11), which deals with the scalar product of the values expressed in Table 3 by the fuzzy numbers in Table 1. The partial products are presented in Table 5, thus ensuring a better understanding of the influences of each criterion on the final score.

The outcome of applying the utility function to each mode is represented by the trapezoidal fuzzy number. Consequently, defuzzification (Eq. 9) is required in order to present the \mathbb{R} domain results (Eq. 9). The outcomes of this ranking are shown in Table 4. Like other multicriteria methods, such as the Analytic Hierarchy Process (AHP), the ranking scores obtained through the utility function do not necessarily follow a predefined scale. The applications in Mangelep et al. (2024), Dua (2023), Kuswanto et al. (2023) and Taherdoost (2023) exemplify this approach to ranking results.

Table 4. Outcome of applying the utility function to transportation modes

Subway	Train	Barge	Bus
0.35	0.23	0.31	0.23

The data characterising the respondents in Rounds 2 to 4 show some convergences, such as: mostly male; 31 to 40 years old; and with university educations. This pattern suggests a relatively stable demographic composition during the earlier stages of the survey. In Round 5, which was the first in-person survey, a change in profile was noted, being predominantly high school or technical college graduates between 18 and 30 years old. This shift may reflect differences in accessibility or engagement levels associated with the change in data collection method. For trip-related aspects, there is also no homogeneity between rounds 2 to 5, highlighting the variability in respondent experiences across survey phases.

With regard to mode use for daily commutes, results were initially noted for the use of only one mode, reaching three modes (two changes) in Round 4. This progression indicates an increasing complexity in travel behaviour, possibly influenced by external factors such as infrastructure or the availability of transport options. This is also where a clash with other collected data appears, such as total trip times not exceeding two hours for all these respondents, suggesting potential inconsistencies in reporting. Throughout the survey, commuting to and from work was the main reason for their trips. For a better understanding of respondent characteristics, as well as trip-related phenomena, Table 5 presents more detailed findings for each round examined in this study.

Table 5. Respondent characteristics and trips

Characteristics		Round 2	Round 3	Round 4	Round 5
Gender	Female	45.2	41.5	34.5	45.4
	Male	54.8	58.5	65.5	54.6
Age Bracket	Up to 17 years old	0.0	0.0	0.0	2.9
	18 to 30 years old	19.6	10.1	14.8	34.0
	31 to 40 years old	26.7	17.1	19.2	19.5
	41 to 50 years old	21.6	22.6	21.2	19.7
	51 to 60 years old	18.0	23.5	20.1	11.5
	Over 60 years old	14.0	26.7	24.6	12.4
	Primary School	0.4	0.5	2.9	21.1
Education	High School Technical College	9.5	8.3	28.1	52.5
	University Graduate	36.2	27.2	33.4	21.4
	Specialisation	32.3	35.0	21.9	2.8
	Master's degree	14.6	24.9	8.0	1.5
	Doctorate	6.9	4.1	5.8	0.8
	None	43.6	48.8	21.5	53.0
	One	22.2	20.7	19.7	30.0
Number of Mode Changes	Two	25.6	24.4	39.8	13.0
	Three	7.7	6.0	15.3	3.3
	Four or more	1.0	0.0	3.8	0.9
	Up to 1 hour	52.0	59.0	35.6	58.0
Total Trip Time	1 to 2 hours	37.8	28.1	42.0	33.1
	2 to 3 hours	8.4	9.7	18.4	7.6
	More than 3 hours	1.8	3.2	4.0	1.3
	Recreation	1.6	3.7	3.3	7.8
Reason for Trip	Health	2.2	4.1	4.4	4.4
	Work	83.5	82.9	78.5	78.1
	Study	4.7	2.3	5.5	8.2
	Other	8.0	6.9	8.2	1.4

Pursuing the main purpose of this study, the findings presented in Table 4 are particularly noteworthy. Originating in the case study, they categorically indicate the predominance of the subway as the mode of choice, with the highest quality among the four transportation options under examination. In order to expand the analytical capacity of the application of the Fuzzy-SAW model, it is essential to provide detailed descriptions of the criteria contributions for each alternative, through the $w_j \cdot r_{ij}$ (Eq. 10) products, observing the most positive and negative for mode quality, from the user standpoint. Consequently, Table 6 presents partial findings that impacted the application of the utility function, which went through a normalisation process in order to allow comparisons on a scale [0-10], with 10.0 being the most important mode choice criterion.

Table 6. Criteria shares in mode ranking

Criteria	Alternatives (Modes of transportation)			
	Subway	Train	Barge	Bus
C01	4.6	5.0	3.9	7.4
C02	1.7	1.7	1.4	1.8
C03	1.8	1.7	1.3	1.8
C04	2.6	2.7	2.7	3.3
C05	2.6	2.7	1.9	2.8
C06	10.0	10.0	10.0	10.0
C07	9.4	8.3	7.1	8.7
C08	2.1	2.3	1.8	2.9
C09	2.2	2.5	1.8	3.1
C10	3.7	3.1	2.8	4.4
C11	3.9	3.5	2.2	4.1
C12	1.2	1.0	0.9	1.2
C13	1.2	1.1	0.8	1.3
C14	1.3	1.7	1.1	2.0

Among users of the assessed modes, safety is the issue that most affects mode quality in their daily commutes, in transit, as well as when entering or leaving vehicles at stations, stops, or terminals. In contrast, the least important trip criterion is maintenance conditions for vehicles and the locations where they start and end their trips. It is interesting to note that the maintenance aspect is necessarily linked to safety, reliability, and accessibility. This indicates a certain lack of knowledge among the respondents about the impacts of this criterion on their commute conditions.

Looking at the forty intermediate values reflecting criteria between the most positive and the most negative, as listed above, 35 are in the 1 to 4 range, indicating a certain homogenisation of other criteria ranked as close to and relatively distant from the two safety-related criteria. The only exception in this intermediate range is the importance of urban bus fares, which is out of step with reality when compared to other mode fares, at almost double the value. It is also worth noting here the preponderance of land modes in Rio de Janeiro, even replacing the three high-capacity trunk modes of transportation. In conceptual terms, buses rank as low-capacity options, with the capillarity of this mode making it a frequent feeder and distributor for high-capacity modes: the subways, railways, and ferries, whose high capacities are sized to meet their demands. A characteristic peculiar to the City of Rio de Janeiro is that its trunk systems connect places of origin to the city centre during peak morning commutes, resulting in extreme time/distance relationships and causing discomfort for users, at the very least. The average distances travelled and the average trip times for each mode examined in this study are shown in Table 7.

Table 7. Average trip distance and time within the city of Rio de Janeiro

	Modes of transportation							
	Subway		Train		Barge		Bus	
	MP	AP	MP	AP	MP	AP	MP	AP
Average distance (km)	13.0	12.9	24.4	27.8	7.7	8.4	9.4	9.4
Average Time (min)	27.1	27.0	41.7	45.2	28.8	25.5	30.2	29.8

Note. MP = morning peak; AP = afternoon peak (Rio de Janeiro, 2018)

It is estimated that 4.17 million passengers are carried each day by bus, while Subway Lines 1 and 2 (some 60 kilometres long) record 837,000 boardings a day (including transfers between lines). Eight train lines (with around 270 kilometres of track) serve 645,000 passengers a day; while four ferry lines carry about 107,000 passengers each day (Rio de Janeiro, 2018). These data illustrate the imbalance in its modes of transportation for Rio de Janeiro, directly impacting user perceptions of its four predominant modes.

In complex decision-making contexts, especially those involving multiple variables, conflicting purposes, or subjective criteria, the use of multicriteria methods is not only relevant, but essential. These methods provide a systematic framework for assessing and selecting alternatives among multiple and often interdependent, factors, underpinning more rational, transparent, and justifiable decisions. More specifically, the use of the Fuzzy-SAW method blends the simplicity of SAW with the flexibility of treating subjective contexts through Fuzzy Theory. In situations involving linguistic perceptions and ambiguities in complex choices, characterised by multiple criteria and uncertainties in judgments, this method offers a robust, adaptable and especially effective approach for modelling the imprecisions found in human assessments.

Through the Fuzzy-SAW method, these expressions of respondent perceptions may be transformed into trapezoidal fuzzy numbers, enabling the mathematical treatment of these uncertainties in a coherent and measurable way. Adding the association of weightings to these types of numbers, thus relating criteria to alternatives, the degree of influence that each criterion exerts on the assessment of the alternatives is determined, reflecting respondent priorities and preferences. Another relevant aspect is that weighting the criteria allows for balanced comparability between modes of transportation, even when the criteria are of different types, in terms of user perceptions.

The IQMU results provide direct input for the formulation and prioritization of urban mobility public policies. First, the identification of the most influential criteria—safety and fare—guides the definition of budgetary and operational priorities: immediate interventions can focus on safety in critical terminals and lines (lighting, surveillance, operational presence) and on targeted fare policies (fare integration, means-tested subsidies), aiming for rapid improvements in user perception. Such measures are supported by the use of composite indicators as instruments of policy influence, provided that their design and dissemination processes are transparent and legitimized, which increases the likelihood of uptake by public managers.

Second, the modal ranking produced by the Fuzzy-SAW method yields an operational metric that can be incorporated into targets and management contracts: perception scores can become KPIs in operating contracts (with bonuses/penalties) and explicit criteria in multiannual plans and urban mobility plans, aligning investments with user experience rather than solely with traditional technical indicators. Instrumenting these indices within municipal governance, however, requires methodological transparency and public disclosure of methods and results to legitimize decisions and reduce resistance.

Third, the limitations identified—differences in respondent profiles between online and in-person rounds and insufficient representativeness in earlier samples—demand measures to avoid decisions based on non-comparable series: we recommend institutionalizing standardized data collection (a municipal observatory or academic partnership), applying sample weights where appropriate, and regularly publishing documentation of methods and uncertainties. A standardized protocol for the design and dissemination of composite indicators facilitates the translation of research into effective municipal management.

Fourth, the results enable territorially targeted and equity-oriented policies: by disaggregating scores by geography, age group, and educational level (as allowed by the survey data), managers can direct interventions to groups and areas with poorer perceptions—e.g., accessibility programs, service provision in deficit corridors, or subsidies for low-income users—thereby contributing to the reduction of mobility inequalities. This targeted use strengthens the social dimension of transport policies by linking technical metrics to tangible population impacts.

Fifth, decision-makers should require sensitivity analyses (as recommended) prior to structural decisions: only when rankings and recommendations prove robust to variations in weights, aggregation methods, and sampling should major resource reallocations be approved. This methodological safeguard protects against unstable policy choices and increases political and public confidence in interventions. Finally, bridging research and municipal management—through open dissemination of indices, citizen participation in priority setting, and post-implementation evaluation cycles—can transform the IQMU from an academic indicator into a governance tool; the literature shows that composite indicators influence policy when integrated into management routines, public communication and accountability mechanisms. Implementing the cycle measure → prioritize → intervene → re-evaluate is a necessary condition for the study's findings to translate into tangible improvements in urban mobility.

4. Conclusions

The main purpose of this paper is to propose a multicriteria approach for modal ranking analyses, for the purpose of translating public transportation user perceptions and subjective concepts into objective and tangible values, providing a quality item ranking expressed through fourteen criteria. This mathematical model was validated through a case study conducted in the City of Rio de Janeiro, using data collected in rounds 2 to 5 for preparing the Urban Mobility Quality Index (IQMU). Although this study focuses on a single city and primarily aims to exemplify and validate the model, several features make the approach transferable to other jurisdictions: a broad spectrum of transport modes; the robust Fuzzy-SAW framework for mathematically representing users' perceptions of urban

mobility quality; and systematic profiling of respondents, which enables cross-referencing of data to produce richer, policy-relevant insights.

From a methodological perspective, it is important to highlight the limited comparability of IQMU results obtained in earlier rounds with those from the current data collection (fifth round). Previous rounds relied on an internet-based questionnaire administered remotely, whereas the present study collected responses in high-passenger-flow locations at boarding and alighting points. This change in data collection context compromises direct comparisons between rounds and requires cautious interpretation of temporal trends. Nonetheless, respondent characteristics remain analyzable: gender, age group, and educational level, as well as trip-related variables such as number of transfers, total travel time, and trip purpose. These attributes allow for within-round stratified analyses and for assessing associations between user profiles and perceived quality of mobility.

An additional methodological concern is that earlier internet-derived samples lacked sufficient statistical power and representativeness to support cross-city comparisons across the four previously recorded rounds or to compare different transport modes reliably. Consequently, the IQMU scores from those rounds should not be used as a benchmark for intercity or intermodal comparisons without appropriate weighting or resampling procedures. The technical procedures involved data collection based on the population of Rio de Janeiro, through a questionnaire using the five-response Likert scale for questions exploring user experiences. First round data treatment included the fuzzification of linguistic expressions in Fuzzy-Integrals and fuzzy numbers, especially in the trapezoidal format, representing the Perceived Quality of the Modes of Transportation. Subsequently, these fuzzy numbers were aggregated through multiple data collection rounds, thus forming the decision matrix for the model. During the application of the utility function, the defined weights were computed by order of importance for users. The outcome of this processing stage ranked the modes of transportation by perceived quality.

Based on these findings, it became apparent that these fourteen criteria can reflect the quality of different moods of public transportation in varying contexts. The numerical values resulting from the mathematical model are trustworthy in terms of the urban realities of Rio de Janeiro, with the subway mode predominant. Criteria related to safety were identified as items that most affect mode quality for users during their daily commutes, in vehicles as well as at stations, stops, and terminals. On the other hand, aspects related to conservation and maintenance were ranked as less important by respondents, which might indicate a certain lack of knowledge about the impacts of these criteria on system safety and reliability. The fare criterion was perceived as very negative for all modes, differing from the others for urban buses.

The application of the Fuzzy-SAW modelling method for complex decision-making contexts that involve multiple variables and subjective criteria, proved essential for providing a systematic framework for the assessment and selection of alternatives, underpinning more rational, transparent, and justifiable decisions. Blending the simplicity of SAW with the flexibility of Fuzzy Theory allowed linguistic perceptions and uncertainties to be treated in robust and adaptable ways, which was particularly effective for modelling the imprecisions found in human assessments. In brief, by quantifying subjective perceptions, this study contributes to a better understanding in greater depth of public transportation from the user standpoint. This is a key factor for the development of more resilient, humanised, and sustainable cities, where mobility is a right accessible to all their citizens.

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Author Contribution

Conceptualization, methodology, and formal analysis were carried out by the authors. Data collection and investigation were conducted collaboratively. All authors contributed to writing, reviewing, and editing the manuscript and have approved the final version for publication.

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. In rounds 2 to 4, consent was requested and ratified by completing the questionnaire; for the fifth round, consent was given in person to the researcher.

Data Availability Statement

The data is protected and not publishable, in accordance with Brazil's Data Protection Law (13.709/2018).

Conflicts of Interest

The authors declare no conflicts of interest. Furthermore, the funders had no role in the study design; data collection, analysis, or interpretation; writing the manuscript; or the decision to publish the results.

Declaration of Generative AI Use

The authors declare that no generative artificial intelligence tools were used in the design, analysis, or writing of this manuscript. All content reflects the original work and intellectual contribution of the authors.

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