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Original Research

Integrated and sustainable performance evaluation of urban rail transit systems using fuzzy sustainability index

Berna Çalışkan

Department of Civil Engineering, Transport Engineering, Istanbul Technical University, Turkey.
Correspondence to: Berna Çalışkan, bernaemir@gmail.com

Abstract: The complexity of prominent dimensions in urban rail transportation sector arises from the involvement of several stakeholders and the various interacting variables for evaluating transportation performance. This study uses a fuzzy logic-based method to present an index-based framework for sustainable performance assessment. The proposed framework presents 4 main indicators which include environmental, economic, financial and social sustainability, 14 sub-indicators, 4 main indicators for transportation system effectiveness with 13 sub-indicators and 1 main indicator for multi modal integration with 6 sub-indicators. The performance ratings and importance weights of the transport sustainability attributes are evaluated using a fuzzy logic approach. A numerical illustration is provided to demonstrate the applicability of the approach. The results show that system capacity (passenger capacity of a route), comfort and customer service (passenger environment and ride quality, maintenance cycle) and multimodal integration (park and ride facilities) were found to be weaker attributes. The proposed methodology facilitates the systematic understanding of the prominent attributes for achieving integrated and sustainable transport performance by using the 'Fuzzy Transport Sustainability Index'.

Keywords: Sustainability index, Fuzzy logic, Performance measurement, Urban rail transit

Introduction

Urban rail transit is a crucial part of the basic urban public transportation system. When considering the realistic urban advancement of all nations, rail transit emerges as a key instrument for urban transportation in industrialized nations and areas due to its benefits, which include low carbon emissions, less land occupation, quick speed, safety and reliability, punctuality and comfort, and mass transit capacity [1].

The development of urban rail transit is regarded as a feasible solution to alleviate the concerns for urban transportation. This work aims to define sustainability in urban public transportation, understand the mechanisms behind sustainable development in urban public transportation, propose a fuzzy sustainability index for creating urban rail transit systems that are socially equitable, environmentally sound and economically viable.

The most common approach to evaluating sustainability consists of indicator systems that assist in grouping each indication according to particular themes pertaining to a community's mission and objectives. By taking long-term effects on the development of urban rail transit into account, sustainability evaluation can be incorporated at the planning level to influence policy and decision-making. The selection of relevant indicators in accordance with the selected scientific framework and assessment dimensions is another prerequisite for building a successful evaluation index system. The proper assessment dimensions and a

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trustworthy, all-encompassing and applicable framework are chosen to form the foundation of the evaluation index system. Indicators for evaluating public transportation sustainability using various criteria have been thoroughly studied by numerous academics in recent years.

Three main parties are involved in public transportation. The government makes reference to the public transportation system, which prioritizes ultimate operational performance while providing public services to satisfy social requirements. The operating companies, on the other hand, usually concentrate on production efficiency in order to maximize output while reducing costs. The expectations held by operators, governments, passengers and among other stakeholders are different. In addition to expecting good service at a reasonable price, passengers' primary concerns are journey time and expense. The assessment of the efficiency of public transportation services is the ultimate performance result, which is passenger flow and passenger miles. Every stakeholder's perspective must be taken into account when assessing the operational success of public transportation due to the varying attitudes and expectations of these parties [2].

Previous studies reveal gaps and shortcomings in facilitating systematic performance evaluation of urban rail transit systems. The following highlights of this study demonstrate the novelty of the proposed approach with the respective gaps identified in the current knowledge:

- Clarify the mechanisms for the sustainable development of urban public transportation.
- Define criteria for assessing the sustainability performance of urban rail transit based on urban rail transit system and network, system capacity, capacity of station elements, comfort and customer service, multimodal integration, environmental, economic, financial and social sustainability indicators.
- This study applies the 'Fuzzy Performance Importance Index' to assess the 'Urban Rail Transit Suitability'.
- This study offers a practical approach to visualize the level of transport sustainability for an integrated, advanced development of public transport by providing a roadmap for decision makers.
- This study applies a fuzzy transport sustainability evaluation framework among urban rail transit systems that do not exist in previous literature.
- This study is the first fuzzy logic based assessment to evaluate the sustainability, system effectiveness of urban rail transit and performance ratings and important weights of urban rail transit in the metropolitan area of Istanbul by the decision maker group (operators, government, transport users).

This remaining sections of this paper are organized as follows. Section 1.1 and Section 1.2 perform a detail analysis of the literature to investigate the important indicators specific to sustainability of urban rail transit and construct a workflow using the fuzzy logic-based approach for an index-based sustainable performance assessment framework. Section 2 presents the research methodology, methods and the flowchart of the methodology adopted step by step for the integrated and sustainable performance evaluation of urban rail transit systems using the fuzzy sustainability index. Section 3 presents the study findings and section 4 discusses the results and concludes with remarks.

1.1 Literature review

Urban rail transit systems require significant capital expenditures as well as high operating costs; therefore, performance evaluation is necessary for effective resource management and adequate service provision. Research on performance measurement in public transport systems has expanded significantly in recent years, with a clear distinction between financial and quality-of-service performance frameworks. Cost efficiency is no longer the only performance metric considered; service quality, which affects ridership attraction and retention, has been drawing increasing attention lately. Performance evaluation is essential for the effective use of resources and adequate provision of services in urban rail transit systems, as these systems require significant capital expenditures and high operating costs [3].

Based on the approaches reviewed in the literature, global research on simulating the sustainability of transportation systems has grown in quality and quantity. To shed light on the methods and analytical tools utilized for more successfully integrate and evaluate sustainability parameters, this article first reviewed various tools and methodologies adopted in the literature, including graphical models [4], economic-based models [5], system dynamics approaches [6], integrated transportation and land use models [7], simulation and decision analysis models [8], environmental impact analysis [9], and life cycle assessment (LCA) [10].

Kusakci et al. [11] used fifty-three variables on the institutional, social, environmental and economic dimensions in order to create a Sustainable Cities Index (SCI) and evaluate the sustainability performance of thirty metropolitan areas in Turkey between 2010 and 2018. The study provides insightful information about urbanization patterns and motivates local governments to make more effort to weigh the advantages and disadvantages of sustainability-related public policies. Kumar and Anbanandam [12] evaluated the current sustainability performance of the freight transportation industry with an index called the "Fuzzy Transportation Environmental and Social Sustainability Index", which is based on a fuzzy multi-criteria decision-making method (MCDM).

Hou et al. [13] reviewed the common metrics used in the sustainable evaluation of public transportation. Average travel time and speed, frequency, service satisfaction, etc. are the most commonly used indicators of system efficiency. In respect to environmental dimension, the most commonly used indicators are energy consumption, greenhouse gas and pollutant emissions. Finally, network coverage, accessibility, vehicle occupancy, human health, etc. are the most common indicators for the social dimension.

A fuzzy logic-based methodology for evaluating sustainable performance was tested by Gandhi and Kant [14], which includes sustainability metrics for rail freight transportation. This study utilizes an index-based framework for sustainable performance assessment with the spherical fuzzy analytic hierarchy process (SF-AHP). Expert consultation and literature analysis are used to produce the thirty-six sustainability indicators. Lazar and Chithra [15] outlined the earlier research in the field of building sustainability assessment methods. They presented the critical sustainability criteria and the corresponding sustainability indicators for the environmental, social and economic dimensions.

From the perspective of operational sustainability, Yang and Liu [2] developed a model for analysing the operational performance of urban rail transit systems in China. From the viewpoint of operators and passengers, this study presents the selected input-output variables and describes a detailed workflow for evaluating sustainable operational performance. Decision criteria that influence passengers' choice of public transportation include the cost of tickets, connections to different modes of transportation, connections between lines, frequency of construction of shared facilities, etc. These selection criteria have a significant impact on how well the urban rail transit system operates overall [2].

We hope that our work will contribute to a better understanding of 'Characterization of methodologies for integrated assessment of urban rail transit sustainability' and we construct a workflow using the fuzzy logic-based approach for an index-based sustainable performance assessment framework. Fuzzy logic is a branch of mathematics that allows a computer to model the real world as the same way that humans do. It provides a simple way to reason with vague, ambiguous and imprecise input or knowledge. Fuzzy set theory is recognized as an important technique for modeling and solving problems [16].

We have identified clear and concise research questions. The following research questions enable to select the appropriate research methodology and design: a). Which subjects, problems or decision indicators are studied? b). What methods are used for evaluating sustainable performance? c). What research methodology is best appropriate to achieve the research aims and objectives? d). Does the proposed methodology facilitate a systematic understanding of the prominent measures to achieve a high level of sustainable transport performance?

To sum up, this study comprehensively explores the systematic assessment of transportation system performance in order to obtain a structured, easily applicable, multidimensional, collaborative model for performance measurement and this study effectively demonstrates the fuzzy logic-based decision making technique for urban rail transit network, system capacity, station element capacity, comfort and customer service, multi-modal integration, environmental, economic, financial and social sustainability.

1.2 Determination of performance indicators

The technique for performance measurement serves as the foundation for the actions that must be taken to identify issues, measure the degree of application of principles, and assess the performance level of the transportation industry. To enable an objective evaluation based on the comparison, it is first important to identify the objectives and the appropriate performance indicators and standards. Then, it is necessary to collect the relevant data and carry out the measurements. In this case, identifying performance indicators is crucial to effectively manage the performance of urban rail transit systems.

The use of sustainability indicators in the assessment and planning of transportation was comprehensively addressed by Litman [17]. Establishing goals is the first step in the evaluation and planning process for transportation. Goals help to define planning objectives, targets and outcomes. Jasti and Ram [18] used fuzzy logic and the analytical hierarchy approach to create a framework specialized by mode that is both integrated and sustainable. The criteria of network system, system and station capacity, comfort, multi-modal integration, and environmental, economic, financial and social sustainability are selected to calculate the performance scoring, transport sustainability weighting and transportation system effectiveness.

The comprehensive performance evaluation model offers consistent representative factors for promoting continual improvement, providing the necessary data to support the decision-making process, supplying long-term consistent profitability and monitoring compliance with regulations. The study's framework consists of 9 performance indicators structured with 33 evaluation metrics (sub-criteria). Figure 1 shows the main and sub criteria of transport sustainability. The development of urban rail transit systems includes the following "collectively structured" objectives.

We proposed 4 main indicators including environmental, economic, financial and social sustainability and 14 sub-indicators, 4 main indicators for the effectiveness of transport system with 13 sub-indicators and 1 main indicator for multimodal integration with 6 sub-indicators. The identified indicators are listed in Table 2. The sub-indicators/ evaluations criteria for urban rail transit are listed. The assignment of ratings to the criteria / evaluations are explained in detail in the following part of Step 2. In each row, the references that refer to previous literature studies are listed.

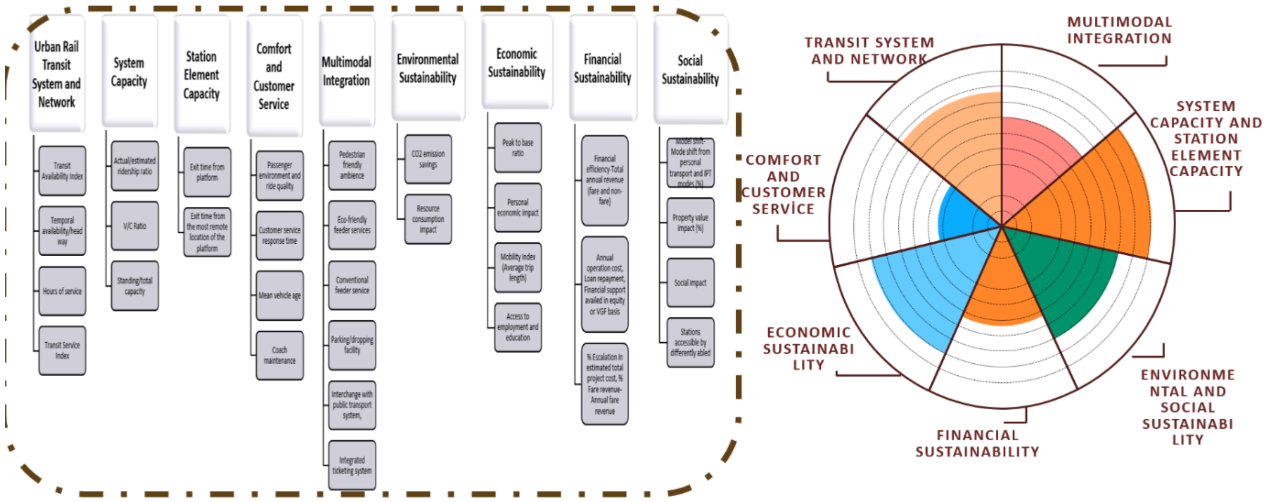

Figure 1. Main and sub criteria of transport sustainability [18]

2. Materials and methods

An extensive model for assessing the performance of urban rail transit is presented in this article. Rajak et al. [19] developed a conceptual model to calculate the Fuzzy Performance Importance and Fuzzy Transport Sustainability Indexes. This methodology is adopted in this study for the performance indicators of urban rail transit system. Lin C.-T. et al. [20] used a similar method to develop the agility index using fuzzy logic. In this method, the importance weights and performance ratings of various agility characteristics evaluated by specialists are expressed in linguistic words. The corresponding fuzzy numbers are then utilized to represent the linguistic values. These fuzzy numbers are then combined into a single fuzzy number, the fuzzy-agility-index (FAI), via a simple arithmetic fuzzy process. Furthermore, the linguistic expression of the agility level is made possible by matching the FAI with suitable linguistics. Finally, the fuzzy performance importance index (FPII) is developed for each agility capability to assist managers in determining the primary risk factors and urge them to implement a suitable action plan to raise the agility level.

The architecture of this study includes 9 performance indicators structured with 33 evaluation criteria (sub-criteria). 9 main indicators proposed by Jasti and Ram [18] were selected for this study. In this study, 4 main indicators (environmental, economic, financial and social sustainability) and 14 sub-indicators, 4 main indicators of transport system effectiveness with 13 sub-indicators and 1 main indicator of multimodal integration with 6 sub-indicators are used, which are distinct from other previous studies. Rajak et al. [19] developed a conceptual model for the performance evaluation of urban rail transit systems using the fuzzy sustainability index. On the basis of extensive research and discussions with experts and practitioners, appropriate performance metrics are created. This approach takes into account the ambiguity and diversity of factor measurement while allowing the consideration of the critical relationships between criteria and decision levels [21]. In order to assess the success of a project or service, this approach can be used to detect and resolve instances in which different stakeholders and service providers have conflicting expectations and goals for performance measurement [22]. For collaborative performance measurement, a committee of three decision makers is selected: D1 (operator), D2 (government) and D3 (transport users). After collecting relevant inputs on linguistic factors from experts and decision makers, the inputs are fuzzified and the Fuzzy Performance Index (FPI) is calculated. The flowchart of the step-by-step methodology applied is presented in Figure 2.

Step 1: Selecting the proper linguistic scale to evaluate the sustainability and system effectiveness of urban rail transit performance ratings and important weights

It is more appropriate to think of fuzziness as a non-probabilistic type of ambiguity when working with humanistic systems. Formulating and conveying quantitative fuzzy variables as linguistic notions requires a basic understanding of fuzzy numbers [23].

Fuzzy logic is characterized by the ad hoc use of language concepts and associated membership functions. Notably, a large number of well-known language phrases along with matching membership functions have been proposed for linguistic evaluation [21]. The importance weights and performance ratings of the transport sustainability qualities are evaluated using linguistic terms. This study has adopted the linguistic scale that Lin et al. [20] used.

As Table 1 illustrates, the following linguistic variables are used to rate the performance of the transport sustainability capabilities and the linguistic assessments employed by decision makers to determine the relative importance of the transport sustainability features.

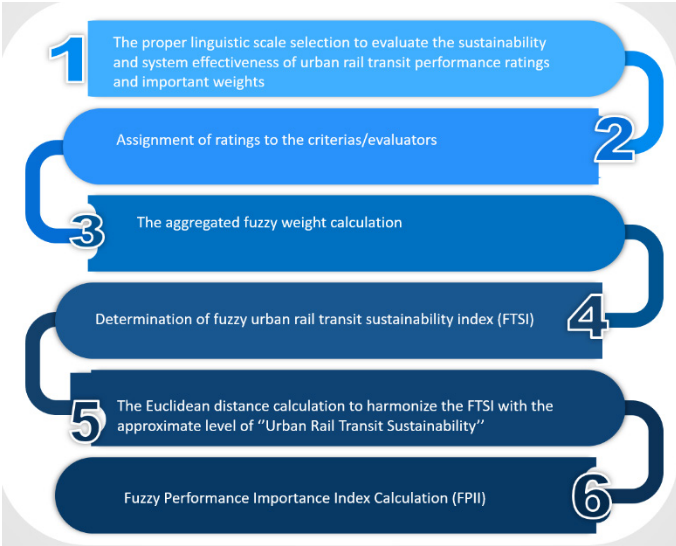

Figure 2. Flowchart of methodology

Table 1. Fuzzy numbers for approximating linguistic variables

Performance rating		Importance weighting	
Linguistic variable	**Fuzzy number**	**Linguistic variable**	**Fuzzy number**
Worst (W)	(0, 0.5, 1.5)	Very low (VL)	(0, 0.05, 0.15)
Very poor (VP)	(1, 2, 3)	Low (L)	(0.1, 0.2, 0.3)
Poor (P)	(2, 3.5, 5)	Fairly low (FL)	(0.2, 0.35, 0.5)
Fair (F)	(3, 5, 7)	Medium (M)	(0.3, 0.5, 0.7)
Good (G)	(5, 6.5, 8)	Fairly high (FH)	(0.5, 0.65, 0.8)
Very Good (VG)	(7, 8, 9)	High (H)	(0.7, 0.8, 0.9)
Excellent (E)	(8.5, 9.5, 10)	Very high (VH)	(0.85, 0.95, 1.0)

Step 2: Assignment of ratings to the criteria/ evaluation criteria

The decision makers used the linguistic terms to directly assess the rating that characterizes the degree of effect/impact of different factors on the sustainability of transportation after defining the linguistic variables and related membership functions to evaluate the performance ratings and the importance weights of the selected criteria. A committee of three decision makers is selected as D1(operator), D2 (government) and D3 (transport users) for the assessment of sustainable urban rail transit in Istanbul metropolitan city. The committee of these three members was invited to fill in the performance and attribute weights online. They were asked to assess the main indicators and sub-indicators by using linguistic variables listed in Table 1. The proposed framework contains 4 main indicators including environmental, economic, financial and social sustainability and 14 sub-indicators, 4 main indicators for the effectiveness of transport system with 13 sub-indicators and 1 main indicator for multimodal integration with 6 sub-indicators. These evaluation criteria are shown in Table 2.

The collection of criteria, which had been identified through scientific means, provides mobility managers and planners seeking to create more sustainable solutions with guidance on which criteria to employ based on available data. The primary set of criteria facilitates the following points and enables the sustainability assessment of different transportation projects both before and during implementation: selecting and ranking various transportation options or regulations, such as determining the relative impacts of different modes of transportation; and monitoring advancements over time and evaluating the sustainability of an ongoing transportation project [53].

Table 2. Linguistic assessments on urban rail transit

Main indicators	Decision			Sub-Indicators		Decision			Aggregate fuzzy ratings (Weight)
	D1	D2	D3		Evaluators	D1	D2	D3	
TSI_1 /Urban Rail Transit System and Network	VH	H	H	TSI_{11}	Service coverage (Lines length/Area km/ km^2) [24]	VH	H	H	(0.7, 0.8, 0.9)
				TSI_{12}	Service Headway (min) [25]	VH	H	H	(0.7, 0.8, 0.9)
				TSI_{13}	Operating hours [26]	VH	H	H	(0.7, 0.8, 0.9)
				TSI_{14}	Travel time savings (min) [27]	H	H	VH	(0.7, 0.85, 1)
TSI_2 /System capacity	VH	H	FH	TSI_{21}	Actual/estimated ridership ratio [28]	VH	VH	M	(0.3, 0.8, 1)
				TSI_{22}	Passenger capacity of a route [29]	VH	H	H	(0.7, 0.85, 1)
				TSI_{23}	Passenger capacity of a vehicle [29]	VH	FH	FH	(0.5, 0.75, 1)
TSI_3 /Station element capacity	VH	M	M	TSI_{31}	Platfom evacuation time [30]	VH	M	M	(0.3, 0.65, 1)
				TSI_{32}	The dwell time [31]	VH	M	M	(0.3, 0.65, 1)
TSI_4 /Comfort and customer service	VH	FH	FH	TSI_{41}	Passenger ride comfort [32]	H	H	VH	(0.7, 0.85, 1)
				TSI_{42}	Customer-centric support services [33]	VH	FH	VH	(0.5, 0.85, 1)
				TSI_{43}	Mean vehicle age [34]	VH	FH	FL	(0.3, 0.7, 1)
				TSI_{44}	Advanced maintenance cycle [35]	VH	H	H	(0.7, 0.85, 1)
TSI_5 / Multimodal integration	H	H	H	TSI_{51}	Pedestrian friendly environments [36]	H	H	VH	(0.7, 0.85, 1)
				TSI_{52}	Feeder buses for rail transit stations [37]	H	H	H	(0.7, 0.8, 0.9)
				TSI_{53}	Potential feeder areas, feeder network design [38]	H	H	H	(0.7, 0.8, 0.9)
				TSI_{54}	Park and ride facilities [39]	H	H	H	(0.7, 0.8, 0.9)
				TSI_{55}	Integration of the urban public transportation system [40]	H	H	H	(0.7, 0.8, 0.9)
				TSI_{56}	Smart and integrated ticketing system [41]	VH	VH	VH	(0.85, 0.95, 1)
TSI_6 / Environmental sustainability	H	H	FH	TSI_{61}	CO2 emission savings (%) (t/day) [42]	H	H	FH	(0.5, 0.75, 0.9)
				TSI_{62}	Energy efficiency [43]	VH	VH	M	(0.3, 0.8, 1)

				TSI_{71}	Peak hour factor [44]	VH	VH	M	(0.3, 0.8, 1)
				TSI_{72}	Total per capita transport expenditures [45]	M	M	VH	(0.3, 0.65, 1)
TSI_7 / Economic sustainability	H	FH	FH	TSI_{73}	Per capita mobility (daily or annual person-miles or trips) [45]	VH	M	M	(0.3, 0.65, 1)
				TSI_{74}	Flexible access to basic services such as education, work, shopping, health and leisure services [45]	M	H	VH	(0.3, 0.75, 1)
				TSI_{81}	Operating expenses [46]	VH	H	L	(0.1, 0.65, 1)
TSI_8/Financial sustainability	VH	H	L	TSI_{82}	Revenue per vehicle kilometer of transit service [46]	VH	VH	L	(0.1, 0.7, 1)
				TSI_{83}	Infrastructure project cost [47]	VH	H	L	(0.1, 0.65, 1)
				TSI_{84}	The operation process (BOT, PFI,PPP, ABS) [48]	VH	H	L	(0.1, 0.65, 1)
				TSI_{91}	Modal shift from private cars to public transport [49]	H	H	M	(0.3, 0.7, 0.9)
TSI_9/Social sustainability	VH	H	L	TSI_{92}	Property value impact (%) [50]	M	M	VH	(0.3, 0.65, 1)
				TSI_{93}	Social impact [51]	M	M	VH	(0.3, 0.65, 1)
				TSI_{94}	Stations accessibility for disabled people [52]	M	M	VH	(0.3, 0.65, 1)

Step 3: Compute aggregate fuzzy ratings for the criteria and the alternatives

A committee consisting of three decision-makers (D1, D2, and D3) is established. Decision makers evaluate the urban rail system in Istanbul metropolitan area. The aggregated fuzzy weights (~ wij) of these three decision makers for each criterion are calculated using Eq (1) [54]. For example, for the criterion PI11 "Transit Availability Index".

$$w_{j1} = \underbrace{min}_{k}(w_{jk1}),\ w_{j2} = \frac{1}{3}\sum_{k=1}^{K} wjk2,\ w_{j3} = \underbrace{max}_{r}(w_{jk3})$$

Eq (1)

The aggregated fuzzy weight is given by wj = (w_{j1}; w_{j2}; w_{j3}) where:

(0.85, 0.95, 1.0), (0.7, 0.8, 0.9), (0.7, 0.8, 0.9)

$$w_{j1} = \underbrace{min}_{k}(0.85, 0.7, 0.7)=0.7$$

$$w_{j2} = \frac{1}{3}\sum_{k=1}^{3}(0.95 + 0.8 + 0.8)= 0.85$$

$$w_{j3}= \underbrace{max}_{k}(1.0,0.9,0.9)=1.0$$

$$\widehat{wj}= (0.7, 0.8, 0.9)$$

Step 4: Determination of fuzzy urban rail transit sustainability index (FTSI)

The FTSI represents the overall level of sustainability and is used for an integrated and sustainable benchmarking of the urban rail transportation system. After being computed at the sub-criterion level, the fuzzy index was extended to the main criterion level. The fuzzy index at sub-criterion level includes a number of performance characteristics.

The definition of the transport sustainability index is given by Eq (2), in the event that Ri and Wi represent the potentiality/ability and the weight of each criterion, respectively:

$$(\text{TS index}) = \sum_{i=1}^{n} (Ri * Wi) \quad \sum_{i=1}^{n} wi=1$$

Eq (2)

Step 5: Calculating the Euclidean distance to harmonize the FTSI with the approximate level of "Urban Rail Transit Sustainability"

In this step, the FTSI values are harmonized with the linguistic label. The most widely used distance method is the Euclidean approach [19]. In the Euclidean distance method, the set of natural-language expressions is defined as shown in Table 4.

Using the Euclidean distance method (Eq (3)), the Euclidean distance D is calculated as follows:

$$D= (TSI, TSIi) =\{\Sigma x\epsilon p, [f_{TSI}(x)- f_{TS}(x)^2] \}^{1/2} \quad \text{Eq (3)}$$

Step 6: The calculation of Fuzzy Performance Importance Index (FPII)

Lin C.-T. et al. [12] applied the Fuzzy Performance Importance Index (FPII) for identification of barriers. The parameters of Transport sustainability are combined with their importance weights and performance ratings. The contribution of a factor increases with increasing FPII. Here is the formula for calculating the FPII. Wijk is the fuzzy importance weight in the aspect of capability of transport sustainability.

$$FPII = FPIIijk = Wijk \times ACijk,$$
$$\text{where, } Wijk= (1,1,1) – Wijk$$

Eq (4)

Then, by using the formulas in Eq. (2), the FPIIs of each performance indicator are obtained as listed in Table 5. For example, the FPII of the metro system and network PI_{11} is calculated as follows:

$FPII_{11} = [(1, 1, 1) − (0.7, 0.8, 0.9)] \times (3, 5, 7)$
$FPII_{11} = (0.1, 0.2, 0.3)\times (3, 5, 7)= (0.3, 1, 2.1)$

Since fuzzy numbers do not always produce a completely ordered collection, as is the case with real numbers, each FPII needs to be ranked [19]. The ranking of the fuzzy number is based on centroid method for membership function (a, b, c) is given in Eq (5), where a, b, c are the lower, middle and upper numbers of triangular fuzzy number [19].

$$\text{Ranking Score} = (a + 4b + c) /6 \quad \text{Eq (5)}$$

3. Results

The determination of fuzzy urban rail transit sustainability index (FTSI) is explained and the definition of the transport sustainability index is given in step 4. A numerical example was given in the following section for the Transit Availability (TS_{11}) criterion.

For instance, the following formula can be used to calculate the fuzzy index for the Transit Availability (TS_{11}) criterion:

TSI_{11} = [(0.7, 0.8, 0.9) × (3, 5, 7) + (0.7, 0.8, 0.9) × (5, 6.5, 8) + (0.7, 0.8, 0.9) × (5, 6.5, 8)+ (0.7,0.85,1) × (5,6.5,8)] /[(0.7, 0.8, 0.9) + (0.7, 0.8, 0.9) + (0.7, 0.8, 0.9) + (0.7, 0.85, 1)]
TSI_{11} =12.6, 20.525, 28.7 /2.8, 3.25, 3.7= (4.5, 6.32, 7.76)

The fuzzy indexes for each of the sub-criteria were calculated using the same equation and displayed in Table 3. The fuzzy urban rail transit sustainability index (FTSI) was calculated as follows.

FTSI = [(0.7, 0.8, 0.9) × (4.5, 6.32, 7.76) + (0.5, 0.8, 1) × (4.07, 5.97, 7.67) + (0.3, 0.65, 1) x (5,8,8) + (0.5, 0.75, 1) × (3,5,7) + (0.7, 0.8, 0.9) × (4.35, 5.96, 7.35)+ (0.5, 0.75, 0.9) × (3,5,7)+ (0.5, 0.7, 0.9) × (5.25, 7.25, 9.5)+ (0.1, 0.65, 1) × (3,5,7)+ (0.3, 0.65, 1) × (4.5, 6.1, 7.77)] / [(0.7, 0.8, 0.9) +(0.5, 0.8, 1)+ (0.3, 0.65, 1)+ (0.5, 0.75, 1)+ (0.7, 0.8, 0.9)+ (0.5, 0.75, 0.9)+ (0.5, 0.7, 0.9)+ (0.1, 0.65, 1)+ (0.3, 0.65, 1)]
FTSI = (4.15, 6.04, 7.66)

According to the fuzzy index of each sub-criteria for the criterion "Urban Rail Transit Sustainability" in Table 3, PI_1, PI_2, PI_3, PI_4, PI_5, PI_6, PI_7, PI_8, PI_9 are the main performance indicators. The lowest sustainability values for the main criteria are gathered for comfort and customer service (PI_4), environmental sustainability (PI_6) and financial sustainability (PI_8). According to Jasti and Ram [18], the PI weights based on priorities are determined by the Analytic Hierarchy Process. The service-oriented PIs Metro System, Network and System Capacity were prioritized by the experts (16,83). Furthermore, the same tendency was also indicated social sustainability (12,96). Close to these PI groups, priority was given to multi-modal integration (12,09). Among the other sustainable performance indicators, economic sustainability was prioritized (11,57), followed by environmental sustainability (10,58). The priority of financial sustainability was ranked lower with a value of 7,66. The least important PI was determined to be comfort at 6,80. When we compared the results of the two studies, although the weights were determined using different methods (fuzzy logic and AHP), comfort and customer service, environmental and financial sustainability have the lowest score.

The transport performance level and the Euclidean distance values are calculated according to Eq (3), which was explained in Step 5.

Table 3. The fuzzy index for each sub-criteria of "Urban Rail Transit Sustainability"

	Performance Indicators	Wij	Weight of Transport Sustainability attributes (Wijk)	Rijk	TSI
PI_1 /Urban rail transit system and network	PI_{11}	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(3,5,7)	(4.5,6.32,7.76)
	PI_{12}		(0.7, 0.8, 0.9)	(5, 6.5, 8)	
	PI_{13}		(0.7, 0.8, 0.9)	(5, 6.5, 8)	
	PI_{14}		(0.7, 0.85, 1)	(5, 6.5, 8)	
PI_2 /System capacity	PI_{21}	(0.5, 0.8, 1)	(0.3, 0.8, 1)	(5, 6.5, 8)	(4.07,5.97,7.67)
	PI_{22}		(0.7, 0.85, 1)	(3,5,7)	
	PI_{23}		(0.5, 0.75, 1)	(5, 6.5, 8)	
PI_3 /Station element capacity	PI_{31}	(0.3, 0.65, 1)	(0.3, 0.65, 1)	(5, 6.5, 8)	(5,8,8)
	PI_{32}		(0.3, 0.65, 1)	(5, 6.5, 8)	
PI_4 /Comfort and customer service	PI_{41}	(0.5, 0.75, 1)	(0.7, 0.85, 1)	(3,5,7)	(3,5,7)
	PI_{42}		(0.5, 0.85, 1)	(3,5,7)	
	PI_{43}		(0.3, 0.7, 1)	(3,5,7)	
	PI_{44}		(0.7, 0.85, 1)	(3,5,7)	
PI_5 /Multimodal integration	PI_{51}	(0.7, 0.8, 0.9)	(0.7, 0.85, 1)	(5, 6.5, 8)	(4.35,5.96, 7.35)
	PI_{52}		(0.7, 0.8, 0.9)	(5, 6.5, 8)	
	PI_{53}		(0.7, 0.8, 0.9)	(5, 6.5, 8)	
	PI_{54}		(0.7, 0.8, 0.9)	(2,3.5,5)	
	PI_{55}		(0.7, 0.8, 0.9)	(3,5,7)	
	PI_{56}		(0.85, 0.95, 1)	(5, 6.5, 8)	
PI_6 /Environmental sustainability	PI_{61}	(0.5, 0.75, 0.9)	(0.5, 0.75, 0.9)	(3,5,7)	(3,5,7)
	PI_{62}		(0.3, 0.8, 1)	(3,5,7)	
PI_7 /Economic sustainability	PI_{71}	(0.5, 0.7, 0.9)	(0.3, 0.8, 1)	(5, 6.5, 8)	(5.25,7.25,9.5)
	PI_{72}		(0.3, 0.65, 1)	(5, 6.5, 8)	
	PI_{73}		(0.3, 0.65, 1)	(3,5,7)	
	PI_{74}		(0.3, 0.75, 1)	(3,5,7)	
PI_8/Financial sustainability	PI_{81}	(0.1, 0.65, 1)	(0.1, 0.65, 1)	(3,5,7)	(3,5,7)
	PI_{82}		(0.1, 0.7, 1)	(3,5,7)	
	PI_{83}		(0.1, 0.65, 1)	(3,5,7)	
	PI_{84}		(0.1, 0.65, 1)	(3,5,7)	
PI_9/Social sustainability	PI_{91}	(0.3, 0.65, 1)	(0.3, 0.7, 0.9)	(3,5,7)	(4.5, 6.1, 7.77)
	PI_{92}		(0.3, 0.65, 1)	(5, 6.5, 8)	
	PI_{93}		(0.3, 0.65, 1)	(5, 6.5, 8)	
	PI_{94}		(0.3, 0.65, 1)	(5, 6.5, 8)	

Table 4. Transport performance level and the Euclidean distance values

Linguistic labeling	Intervals		Formula	D
Excellent Performance Level	[EPL (7, 8.5, 10)]	(TSI, EPLi)	$\{(4.15-7)^2 + (6.04-8.5)^2 + (7.66-10)^2\}^{1/2}$	4,43
Good Performance Level	[GPL (5.5, 7, 8.5)]	(TSI, GPLi)	$\{(4.15-5.5)^2 + (6.04-7)^2 + (7.66-8.5)^2\}^{1/2}$	1,86
Middle Performance Level	[MPL (3.5, 5, 6.5)]	(TSI, MPLi)	$\{(4.15-3.5)^2 + (6.04-5)^2 + (7.66-6.5)^2\}^{1/2}$	1,69
Low Performance Level	[LPL (1.5, 3, 4.5)]	(TSI, LPLi)	$\{(4.15-1.5)^2 + (6.04-3)^2 + (7.66-4.5)^2\}^{1/2}$	5,12
Very Low Performance	[VLPL (0, 1.5, 3)]	(TSI,VLPLi)	$\{(4.15-0)^2 + (6.04-1.5)^2 + (7.66-3)^2\}^{1/2}$	7,72

Therefore, the transportation performance level can be determined as the "Middle performance level" by comparing a linguistic label with the minimum D value, which is found as 1,69 (Figure 3). Dotted line shows the FTSI (4.15, 6.04, 7.66) values in the diagram. As a result of this calculation step, these values correspond to the 'Middle Performance Level'.

Fuzzy Performance Importance Index are calculated for 'Urban Rail Transit Sustainability' using Eq (4), which was explained in step 6.

Table 5 displays the ranking scores for the fuzzy performance importance indexes, which was determined using the aforementioned principle. A boundary value of 1.05 was established to identify the indicators that impedes progress or achievement and to differentiate them from the others based on the ranking scores. Four indicators are under the threshold value that have to be improved and contribute significantly to reaching performance levels. These indicators are named as (1) PI_{22} Passenger capacity of a route, (2) PI_{41} Environment of passenger and ride quality, (3) PI_{44} Advanced maintenance cycle and (4) PI_{54} Parking/dropping facility.

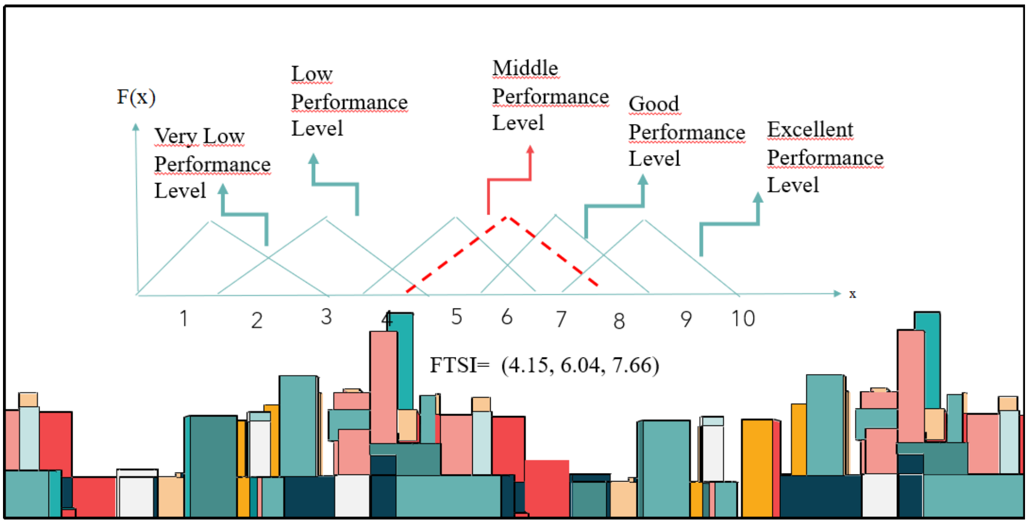

Figure 3. Linguistic levels to match fuzzy index

Table 5. Fuzzy performance importance indexes of 'Urban Rail Transit Sustainability' attributes.

Performance indicators	Aggregated fuzzy performance ratings	Wijk = [(1, 1, 1)-Wijk]	FPII	Ranking score
PI_{11}	(3,5,7)	(0.1, 0.2, 0.3)	(0.3, 1, 2.1)	1,07
PI_{12}	(5, 6.5, 8)	(0.1, 0.2, 0.3)	(0.5, 1, 2.4)	1,15
PI_{13}	(5, 6.5, 8)	(0.1, 0.2, 0.3)	(0.5, 1, 2.4)	1,15
PI_{14}	(5, 6.5, 8)	(0, 0,15, 0,3)	(0,0.975, 2.4)	1,05
PI_{21}	(5, 6.5, 8)	(0, 0,2, 0,7)	(0,1.3, 5.6)	1,80
PI_{22}	(3,5,7)	(0, 0,15, 0,3)	(0,0.75, 2.1)	0,85*
PI_{23}	(5, 6.5, 8)	(0, 0.25, 0.5)	(0,1.625, 4)	1,75
PI_{31}	(5, 6.5, 8)	(0, 0,35, 0,7)	(0,2.275, 5.6)	2,45
PI_{32}	(5, 6.5, 8)	(0, 0,35, 0,7)	(0,2.275, 5.6)	2,45
PI_{41}	(3,5,7)	(0, 0,15, 0,3)	(0,0.75, 2.1)	0,85*
PI_{42}	(3,5,7)	(0, 0,15, 0,5)	(0, 0.75, 3.5)	1,08
PI_{43}	(3,5,7)	(0, 0,3, 0,7)	(0, 1.5, 4.9)	1,82
PI_{44}	(3,5,7)	(0, 0,15, 0,3)	(0, 0.75, 2.1)	0,85*
PI_{51}	(5, 6.5, 8)	(0, 0,15, 0,3)	(0, 0.975, 2.4)	1,05
PI_{52}	(5, 6.5, 8)	(0.1, 0.2, 0.3)	(0.5, 1, 2.4)	1,15
PI_{53}	(5, 6.5, 8)	(0.1, 0.2, 0.3)	(0.5, 1, 2.4)	1,15

PI_{54}	(2,3.5,5)	(0.1, 0.2, 0.3)	(0, 0.7, 1.5)	0,72*
PI_{55}	(3,5,7)	(0.1, 0.2, 0.3)	(0.3, 1, 2.1)	1,07
PI_{56}	(5, 6.5, 8)	(0.1, 0.2, 0.3)	(0.5, 1.3, 2.4)	1.35
PI_{61}	(3,5,7)	(0.1, 0.25, 0.5)	(0.3, 0.75, 3.5)	1,13
PI_{62}	(3,5,7)	(0, 0.2, 0.7)	(0, 1, 4.9)	1,48
PI_{71}	(5, 6.5, 8)	(0, 0,2, 0,7)	(0, 1.3, 5.6)	1,80
PI_{72}	(5, 6.5, 8)	(0, 0,35, 0,7)	(0,2.275, 5.6)	2,45
PI_{73}	(3,5,7)	(0, 0.35, 0.7)	(0, 1.75, 4.9)	1,98
PI_{74}	(3,5,7)	(0, 0.25, 0.7)	(0, 1.25, 4.9)	1,65
PI_{81}	(3,5,7)	(0, 0.35, 0.9)	(0, 1.75, 6.3)	2,22
PI_{82}	(3,5,7)	(0, 0.3, 0.9)	(0, 1.5, 6.3)	2,05
PI_{83}	(3,5,7)	(0, 0.35, 0.9)	(0, 1.75, 6.3)	2,22
PI_{84}	(3,5,7)	(0, 0.35, 0.9)	(0, 1.75, 6.3)	2,22
PI_{91}	(3,5,7)	(0.1, 0.3, 0.7)	(0.3, 1.5, 4.9)	1,87
PI_{92}	(5, 6.5, 8)	(0, 0,35, 0,7)	(0, 2.275, 5.6)	2,45
PI_{93}	(5, 6.5, 8)	(0, 0,35, 0,7)	(0, 2.275, 5.6)	2,45
PI_{94}	(5, 6.5, 8)	(0, 0,35, 0,7)	(0, 2.275, 5.6)	2,45

4. Discussion and conclusions

Initiatives for sustainable transportation have a positive impact on communities all over the world. They promote trade and international collaboration between nations, as well as sustainable economic growth and social welfare. 'Transforming Transport Systems for a Sustainable Future' is essential to guide megacities in developing condition that are conducive to sustainability. In a complicated transport system, however, it is very difficult to create a list of sufficient indicators. An equitable, livable and sustainable development necessitates indicators that are well-founded, few in number, comprehensive in scope, accessible at an affordable cost and that incorporate the characteristics linked to the interplay of institutional, social, economic and environmental aspects. The Ministry of Environment and Urban Planning in Turkey, and metropolitan municipalities, has jointly launched the 'Sustainable Cities Program' aiming to improve economic, financial, environmental and social sustainability of cities.

The sustainability performance of urban rail transportation was assessed using a fuzzy-based methodology, as explained in this article. In order to demonstrate transport sustainability, this research aims to define the sustainability of public transportation, clarify the mechanisms behind the sustainable development of urban public transportation, and offer an index system and assessment model. This research integrates the assessment criteria, index dimensions, assessment methods and study objectives from previous research on the assessment of sustainability in public transportation. Due to the vague and ambiguous indicators that exist within transport sustainability assessment, fuzzy logic provides a useful tool that eliminates the drawbacks such as vagueness, uncertainties, ambiguity, and impreciseness.

By comparing with previous studies, it is understood that the concept of sustainable performance evaluation has not yet been fully realized in the context of urban rail transit systems. Therefore, there is still a long way to go to incorporate such methods into an adaptable, applicable performance evaluation framework that includes environmental, economic, financial and social sustainability indicators. The aspects of achieving integrated and sustainable transport performance are given only a limited amount of attention, even in the transport appraisal guidelines, which represents an opportunity especially for the development of urban rail transit systems.

The aims and vision of a community can be divided into specific sustainability themes or dimensions, and applicable performance metrics and indicators can be found depending on the goal and corresponding objectives. A committee of three decision makers is selected as D1(operator), D2 (government) and D3 (transport users) for collaborative performance measurement. Decision makers evaluate the urban rail system in Istanbul Metropoliten area. The study's inputs are allocated to take into account a group of stakeholders with different level of expertise and skills as well as their own benefits, preferences and goals in developing a sustainable urban rail transit system for a metropolitan city. From the perspective of influence and significance, this study proposes a fuzzy logic-based method for sustainable performance assessment that will help for developing a guide for "Developing a Transit Performance Measurement System".

Indicators make it easier to set goals, evaluate a particular organization or jurisdiction, foresee obstacles, identify trends and developments, set benchmarks, and evaluate alternatives. Quantitative revelation is essential for conducting benchmarking exercises and comparisons. In addition, qualitative monitoring is required to describe the benefits of different transport options and alternatives for operators, government and the public. Indicators that balance quantitative and qualitative aspects are necessary to achieve both goals. For study limitations, the number of evaluators should be increased to offer more reasonable solutions to decision makers.

The research begins with the collection of input ratings and weights from experts and decision makers. A fuzzy logic technique was adopted in the study because standard monitoring of transportation sustainability performance is beset with vagueness and uncertainty. Triangular fuzzy numbers are utilized in performance evaluations. The inputs are fuzzified, and the FTSI is (4.15, 6.04, 7.66). Based on the calculation of Euclidean distance, the transportation performance can be determined as the "Middle performance level" by comparing a linguistic label with the minimum D, which was found to be 1,69. The calculated result was validated using the standard crisp technique. In addition to calculating the transportation sustainability index, weaker areas were also identified for improvement. The FPII of the transportation sustainability parameters was calculated. The results show that system capacity (passenger capacity of a route), comfort and customer service (passenger environment and ride quality, maintenance cycle) and multimodal integration (park and ride facilities) were found to be weaker attributes.

A numerical illustration is provided to demonstrate the applicability of the approach. The strength of our approach lies in its ability to evaluate the sustainability of transportation systems using incomplete or partial data and can be applied to any type of enterprise/region. Cities can actually use the suggested method when assessing and choosing environmentally friendly transportation options, which should be carefully selected because the decision-making process depends on the number of participants and their level of subject-matter competence.

Urban rail transit projects are importantly privileged of public transit system for metropolitan revelation, urban and regional growth, and strategic transformation by driving forward step improvements in production and connectivity that promote societal and economic advancement from the perspectives of local sustainability, urban spatial fairness, public benefits, and other factors. The proposed methodology facilitates a systematic understanding of the prominent policies for achieving extremely high sustainable transport performance.

The transportation performance measures were taken based on the urban rail transit system and network, system capacity, station element capacity, comfort and customer service, multimodal integration, environmental, economic, financial and social sustainability indicators. These crucial components served as the critical principles for structuring the assessment approach. Four indicators are under the threshold value that have to be improved and contribute significantly to reaching performance levels. These indicators are: (1) System capacity PI_{22} Passenger capacity of a route, (2) Comfort and customer service PI41 environment of passenger and ride quality, (3) PI44 Advanced maintenance cycle and (4) Multimodal integration PI54 parking/dropping facility.

This modelling methodology offers a practical approach to visualize the level of transport sustainability for an integrated, advanced development of public transport by providing a roadmap for decision makers. It is vital to distinguish the relevant indicators that can be used to effectively and progressively develop the sustainability dimensions of transportation system. We are aimed to analyze the methods for evaluating sustainable performance, to identify the appropriate research methodology that best achieve the research aims and to propose a methodology that facilitates systematic understanding of the prominent policies for achieving high levels of sustainable transport performance.

For future developments, this framework may also be utilized for the selection of alternative urban rail transit project to have a comparative analysis of the future performance of these projects in terms of environmental, economic, financial and social sustainability. In addition, the framework of this study can be adapted for public-private partnership stakeholders by selecting different decision-making groups (consultants/advisors, contractors, project companies). Therefore, it is necessary to develop and apply more innovative solutions and sophisticated approaches to monitor, analyze and plan urban rail transit systems by aggregating and synthesizing the data of main/sub-indicator to improve the transport sustainability through data-driven reasoning and by selecting different decision-making groups.

Declaration of competing interest

The author declares that there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this research.

Availability of data and materials

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Ethics declaration

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References

[1] Chang-fu H., Yuan X. Research on the role of urban rail transit in promoting economic development. *Procedia Engineering*. 2011; 21: 520-525. doi: 10.1016/j.proeng.2011.11.2046.

[2] Yang X., Liu J. Sustainability in the evaluation of urban rail transit considering both firms and passengers perspectives: A dynamic network data envelopment analysis approach. *Research in Transportation Business & Management.* 2023; 51:101071. doi: 10.1016/j.rtbm.2023.101071.

[3] Awad F.A., Graham D.J., AitBihiOuali L., Singh R. Performance of urban rail transit: a review of measures and interdependencies. *Transport Reviews*. 2023; 43: 698-725. doi: 10.1080/01441647.2023.2166146.

[4] Sichigea, M., Circiumaru, D., Brabete, V., Barbu, C.M. Sustainable Transport in the European Union: Exploring the Net-Zero Transition through Confirmatory Factor Analysis and Gaussian Graphical Modeling. *Energies*. 2024; 17(11): 2645. doi: 10.3390/en17112645.

[5] Zheng, J., Palombo, C.A., McCahill, C., O' Hara, R. , Garrick, N. Quantifying the Economic Domain of Transportation Sustainability. *Transportation Research Record*. 2011; 2242(1):19-28. doi: 10.3141/2242-03.

[6] Fontoura, W. B., Ribeiro, G. M. System Dynamics for Sustainable Transportation Policies: A Systematic Literature Review. *urbe. Revista Brasileira de Gestão Urbana*. 2021;13: e20200259. doi:10.1590/2175-3369.013.e20200259.

[7] Yigitcanlar, T., Dur, F. Developing a Sustainability Assessment Model: The Sustainable Infrastructure, Land-Use, Environment and Transport Model. *Sustainability*. 2010; 2(1): 321-340. doi:10.3390/su2010321.

[8] Jeppesen, S.L. Decision Simulation Technique (DST) as a scanning tool for exploring and explicating sustainability issues in transport decision making. *Proceedings of the 53rd Annual Meeting of the ISSS - 2009*, Brisbane, Australia. 2009; 1(1). Available from: https://journals.isss.org/index.php/proceedings53rd/article/view/1130/419. [Accessed January 2024].

[9] Joumard, R., Gudmundsson, Henrik. Indicators of environmental sustainability in transport, An interdisciplinary approach to methods. *European Commission*. 2010. Available from: https://hal.science/hal-00492823. [Accessed March 2024].

[10] Eckelman, M.J. Life cycle assessment in support of sustainable transportation. *Environmental Research Letters*. 2013; 8(2). doi: 10.1088/1748-9326/8/2/021004.

[11] Kusakci S., Yilmaz M.K., Kusakci A.O., Sowe S., Nantembelele F.A. Towards sustainable cities: A sustainability assessment study for metropolitan cities in Turkey via a hybridized IT2F-AHP and COPRAS approach. *Sustainable Cities and Society*. 2022; 78: 103655. doi: 10.1016/j.scs.2021.103655.

[12] Kumar A., R. Anbanandam. Assessment of environmental and social sustainability performance of the freight transportation industry: An index-based approach. *Transport Policy*. 2022; 124: 43-60. doi: 10.1016/j.tranpol.2020.01.006.

[13] Hou X., Lv T., Xu J., Deng X., Liu F., Lee Lam J.S., Zhang Z., Han X. Evaluation of urban public transport sustainability in China based on the Driving Force-Pressure-State-Impact-Response (DPSIR) framework—A case study of 36 major cities. *Environmental Impact Assessment Review*. 2023; 103: 107263. doi: 10.1016/j.eiar.2023.107263.

[14] Gandhi N., Kant R. Evaluation of sustainability performance of the rail freight transportation: An index-based analysis. *Materialstoday: Proceedings.* 2023; doi: 10.1016/j.matpr.2023.01.193.

[15] Lazar N., Chithra K. Benchmarking critical criteria for assessing sustainability of residential buildings in tropical climate. *Journal of Building Engineering*. 2022; 45: 103467. doi: 10.1016/j.jobe.2021.103467.

[16] Kahraman, C. Multi-Criteria Decision Making Methods and Fuzzy Sets. In: Kahraman, C. (eds) *Fuzzy Multi-Criteria Decision Making*. Springer Optimization and Its Applications, vol 16. Boston, MA: Springer; 2008. doi: 10.1007/978-0-387-76813-7_1.

[17] Litman, T. Developing Indicators for Sustainable and Livable Transport Planning. Victoria Transport Policy Institute. 2024. Available from: https://www.vtpi.org/wellmeas.pdf. [Accessed July 2024].

[18] Jasti P.C., Ram V.V. Integrated and Sustainable Benchmarking of Metro Rail System Using Analytic Hierarchy Process and Fuzzy Logic: A Case Study of Mumbai. *Urban Rail Transit*. 2019; 5: 155-171. doi: 10.1007/s40864-019-00107-1.

[19] Rajak S., Parthiban P., Dhanalakshmi R. Sustainable transportation systems performance evaluation usingfuzzy logic. *Ecological Indicators*. 2016; 71: 503-513. doi: 10.1016/j.ecolind.2016.07.031.

[20] Lin, C.-T., Chiu, H., Tseng, Y.-H. Agility evaluation using fuzzy logic. *Internal Journal of Production Economics*. 2006; 101 (2): 353-368. doi:10.1016/j.ijpe.2005.01.011.

[21] Lin, C.-T., Chen C.-T. New Product Go/No-Go Evaluation at the Front End: A Fuzzy Linguistic Approach. *IEEE Transactions on Engineering Management*. 2004; 51(2): 197-207. doi: 10.1109/TEM.2003.822458.

[22] Quick, K. S. Public Participation in Transportation Planning. In: Mark Garrett (ed.) *Encyclopedia of Transportation: Social Science and Policy*. Thousand Oaks, CA: Sage Publications. 2014. p. 1132-37.

[23] Dhingra, M., Chattopadhyay S. A fuzzy approach

for assessment of smart socio-cultural attributes of a historic urban landscape: Case study of Alwar walled city in India. *Sustainable Cities and Society*. 2021; 69: 102855. doi: 10.1016/j.scs.2021.102855.

[24] Diana, M., Daraio, C. Performance indicators for urban public transport systems with a focus on transport policy effectiveness issues. *12th WCTR conference paper*. 2010. Available from: https://www.researchgate.net/publication/235910939. [Accessed March 2024].

[25] Esfeh, M.A., Saidi, S., Wirasinghe, S.C., Kattan, L. Waiting time and headway modeling considering unreliability in transit service. *Transportation Research Part A: Policy and Practice*. 2022; 155: 219-233. doi: 10.1016/j.tra.2021.11.015.

[26] Aghajanzadeh, M., Aghabayk, K., Esmailpour, J., Gruyter, C.D. Importance – Performance Analysis (IPA) of metro service attributes during the COVID-19 pandemic. *Case Studies on Transport Policy*. 2022; 10(3): 1661-1672. doi: 10.1016/j.cstp.2022.06.005.

[27] Pineda, C., Lira, B.M. Travel Time Savings Perception and Well-Being through Public Transport Projects: The Case of Metro de Santiago. *Urban Science*. 2019; 3(1): 35. doi: 10.3390/urbansci3010035.

[28] Hong, Y., Xie, K., Ishak, S., Ma, Q., & Yang, L. Development of guidelines for collecting transit ridership data (Publication No. FHWA/VTRC 22-R22). *Virginia Transportation Research Council*. 2022; Available from: https://digitalcommons.odu.edu/msve_fac_pubs/71/. [Accessed October 2024].

[29] Leurent, F. Transport capacity constraints on the mass transit system: a systemic analysis. *European Transport Research Review*. 2011; 3: 11-21. doi: 10.1007/s12544-011-0046-5.

[30] Fernandez, R., Allard, P., Seriani, S. Pedestrian Microsimulation of Metro-bus Interchanges. A Case Study in Santiago De Chile. *European Transport Conference 2010*; Glasgow, Scotland. Available from: https://www.researchgate.net/publication/263890518. [Accessed May 2024].

[31] Yan, L., Si-ui, N., Yue, G., Cai-Hua, Z., Duo, L. Detection and analysis of transfer time in urban rail transit system using WIFI data. *Transportation Letters*. 2023; 15(7): 634-644. doi: 10.1080/19427867.2022.2079173.

[32] Peng, Y., Zhou, J., Fan C., Wu, Z., Sun, D., Lin, Y., Xu, D., Xu, Q. A review of passenger ride comfort in railway: assessment and improvement method. *Transportation Safety and Environment*. 2022; 4(2). doi: 10.1093/tse/tdac016.

[33] Sheth, J.N., Jain, V., Ambika, A. The growing importance of customer-centric support services for improving customer experience. *Journal of Business Research*. 2023; 164: 113943. doi: 10.1016/j.jbusres.2023.113943.

[34] Purnamawati, F., Radam, I.F. The Correlation between Vehicle Age and Vehicle Operating Cost of Public Transportation in Banjar Regency. International *Journal of Advances in Scientific Research and Engineering*. 2019; 5(9): 115-125. doi: 10.31695/IJASRE.2019.33524.

[35] Xu, Y., Qiao, Q., Wu, R., Zhou, Z. Advanced maintenance cycle optimization of urban rail transit vehicles. *Advances in Mechanical Engineering*. 2019; 11(2). doi: 10.1177/1687814019827113.

[36] Aromal, V., Naseer, M.A. A methodology for the identification of significant factors for the improvement of pedestrian facilities in an urban area. *Journal of Urban Management*. 2022; 11(3): 353-364. doi: 10.1016/j.jum.2022.04.007.

[37] Yu, X., Bi, Y., Chen, P., Liu, X. Determining a Key Service Area of Feeder Buses for Rail Transit Station Based on Potential Railway Demand. *KSCE Journal of Civil Engineering*. 2023; 27: 5338-5349. doi: 10.1007/s12205-023-0607-x.

[38] Tabassum, S., Tanaka, S., Nakamura, F., Ryo, A. Feeder Network Design for Mass Transit System in Developing Countries (Case study of Lahore, Pakistan). *Transportation Research Procedia*. 2017; 25: 3129-3146. doi:10.1016/j.trpro.2017.05.343.

[39] Liu, H., Li, Y., Li, J. Hou, B., Zhao, S. Optimizing the Location of Park-and-Ride Facilities in Suburban and Urban Areas Considering the Characteristics of Coverage Requirements. *Sustainability*. 2022; 14(3): 1502. doi: 10.3390/su14031502.

[40] Solecka, K., Zak, J. Integration of the urban public transportation system with the application of traffic simulation. *Transportation Research Procedia*. 2014; 3: 259-268. doi: 10.1016/j.trpro.2014.10.005.

[41] *The Benefits of Simplified and Integrated Ticketing in Public Transport*. Passenger Transport Executive Group. 2009. Available from: https://www.urbantransportgroup.org/system/files/general-docs/integratedticketingreportFINALOct09.pdf. [Accessed March 2024].

[42] Jasti, P.C., Ram, V. Estimation of CO2 Emission Savings from a Metro Rail System Using Different Methodologies: A Case Study of Mumbai, India. *European Transport*. 2021; 81. doi: 10.48295/ET.2021.81.2.

[43] XIAO, X., Zhong, Z.,Wang, Y., Zhang, C., WU, H. Research on Energy Efficiency Evaluation of Urban Rail Transit Based on DEA-BCC Model. *IOP Conference Series: Earth and Environmental Science*. 2019; 435. doi:10.1088/1755-1315/435/1/012038.

[44] Li, J., Han, L., Chen, C. Impact of data resolution on peak hour factor estimation for transportation decisions. *Central European Journal of Engineering*. 2013; 3: 732-739. doi: 10.2478/s13531-013-0121-x.

[45] Niskota, A.D., Perujo, A., Pregl, M. Indicators to Assess Sustainability of Transport Activities, Part 1: Review of the Existing Transport Sustainability Indicators Initiatives and Development of an Indicator Set to Assess Transport Sustainability Performance. *JRC Scientific and Technical Reports*. 2007. doi:

10.2788/54736.
[46] Buehler, R., Pucher, J. Making public transport financially sustainable. *Transport Policy*. 2011; 18(1): 126-138. doi:10.1016/j.tranpol.2010.07.002.
[47] Rail infrastructure project costing in New South Wales. *New South Wales Parliamentary Library cataloguing-in-publication data*. Legislative Council. General Purpose Standing Committee No. 3; Chapter 2 Project cost estimation. 2012. Available from: https://www.parliament.nsw.gov.au/lcdocs/inquiries/1706/120308%20Final%20%20report%20Rail%20costings.pdf. [Accessed September 2024].
[48] Sun, J., Chen, T., Cheng, Z., Wang, C., Ning, X. A financing mode of Urban Rail transit based on land value capture: A case study in Wuhan City. *Transport Policy*. 2017; 57: 59-67. doi: 10.1016/j.tranpol.2017.03.014.
[49] Urbanek, A. Potential of modal shift from private cars to public transport: A survey on the commuters' attitudes and willingness to switch – A case study of Silesia Province, Poland. *Research in Transportation Economics*. 2021; 85: 101008. doi: 10.1016/j.retrec.2020.101008.
[50] Gallo, M. The Impact of Urban Transit Systems on Property Values: A Model and Some Evidences from the City of Naples. *Journal of Advanced Transportation*. 2018. doi: 10.1155/2018/1767149.
[51] Xiahou, X., Tang, L., Yuan, J., Zuo, J., Li, Q. Exploring social impacts of urban rail transit PPP projects: Towards dynamic social change from the stakeholder perspective. *Environmental Impact Assessment Review*. 2022; 93: 106700. doi: 10.1016/j.eiar.2021.106700.
[52] Nawagawong, W., Techapeeraparnich, W. Providing facilities to improve accessibilities to railway station for all. *MATEC Web of Conferences*. 2017; 138. doi: 10.1051/matecconf/201713807013.
[53] Kraus, L., Proff H. Sustainable Urban Transportation Criteria and Measurement—A Systematic Literature Review. *Sustainability*. 2021; 13(13) : 7113. doi: 10.3390/su13137113.
[54] Nadaban, S., Dzitac, S., Dzitac, I. Fuzzy TOPSIS: A General View. *Procedia Computer Science*. 2016; 91: 823-831. doi: 10.1016/j.procs.2016.07.088.