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Assessing sustainability indicators of public transportation using PAHP

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ABSTRACT

Sustainable public transport is vital for cities' growth and development. Enhancing public transit will boost demand, ensure balanced sustainability, satisfy users and operators, and help achieve sustainability goals. This requires finding a general framework to determine the priorities that accomplish the goal of sustainability and integration of the transportation system. To evaluate this complex problem, this study used the new technique of Multi-criteria decision-making (MCDM), which is the Parsimonious Analytical Hierarchy Process (PAHP) and the traditional Analytical Hierarchy Process (AHP) in two stages to streamline. The main objective of applying PAHP in the decision-making process is to reduce the number of pairwise comparisons required and prioritize 44 comprehensive indicators of the essential dimensions of sustainability in public transportation. This makes PAHP particularly efficient and less cognitively demanding for experts while still providing robust and reliable prioritization of criteria. The findings highlight that travel time, ticket prices, emissions, and traffic management are the most critical social, economic, environmental, and technical indicators. This approach streamlines evaluation and offers policymakers a clear roadmap for prioritizing sustainability measures in public transit. The implications of this work suggest that future development efforts should focus on enhancing these prioritized indicators to achieve a more sustainable public transportation system.

1. Introduction

Public transportation is pivotal in promoting social and economic progress by enhancing mobility, recognized as one of humanity's fundamental needs [1,2]. It facilitates the efficient movement of people and goods, thereby contributing to a nation's economic vitality. Furthermore, public transportation fosters increased productivity and economic growth through reductions in transportation costs, expenses related to roads and parking facilities, vehicle operating costs, accidents, and pollution [3–5]. It also addresses social needs and delivers transit services, crucial in connecting urban and rural areas, airports, train stations, and ports. The public transportation sector also generates employment opportunities for various roles, including operator teams [6,7]. Diverse definitions of sustainability abound from multiple sources, causing inconsistencies in assessment [8]. Public transportation influences diverse facets of society, such as the economy, mobility, development, quality, government funding, the environment, and quality of life, which hold importance [9,10]. Grasping factors influencing individuals' transportation choices in varied regions is essential for understanding travel behavior [11]. Sustainable development and transportation are interconnected; globally, cities face traffic congestion from heavy car dependence, resulting in environmental, noise, and accident-related expenses [3,12,13,14,15]. To overcome these issues, transport planners and researchers' resolutions mostly revolve around introducing advanced mobility (e.g., electric vehicles [16], autonomous vehicles [17–20], and shared autonomous vehicles [21,22]) or introducing new roadways and infrastructure (e.g., capacity increment), but that may not ensure the sustainability of transport system on the global level. These four domains are sustainability challenges, especially in the energy sector. Transport energy significantly contributes to environmental pollution, accounting for about 25 % of total CO_2 emissions related to climate change [23]. Evaluating the sustainability of public transportation requires a comprehensive assessment of various criteria and sub-criteria. Identifying and prioritizing these factors is essential for enhancing public transportation systems' sustainability [24].

MCDM methodologies offer valuable tools for evaluating transportation service performance by balancing goals, risks, and constraints [25,26]. These models assess alternatives based on multiple criteria to identify the optimal transportation options [27]. Since public transportation planning is deliberated as a strategic decision for public and

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private sectors, it is a decision-making technique that helps identify the optimal alternative by considering multiple criteria and prioritizing alternatives [28]. It involves decision-making and acknowledging various, often conflicting, criteria and alternatives. Primarily, these methods seek to identify the optimal transportation option, fulfilling diverse criteria and multiple objectives [29].

AHP is the most applicable decision-making method in transportation, which, while effective, can become cumbersome and time-consuming when dealing with many criteria [30]. This approach enables the translation of subjective opinions through pairwise comparisons, uncovers and rectifies logical inconsistencies into quantifiable relations, and fosters more rational, transparent, and understandable decisions [31,32].

PAHP is a streamlined version of AHP that reduces the complexity and number of required pairwise comparisons. It also aims to provide a more efficient and practical approach to evaluating the sustainability of public transportation systems [33].

Several vital considerations drive the decision to utilize PAHP alongside AHP in this research. It is simplifying the complex decision-making process by reducing the pairwise comparisons required in traditional AHP, making the evaluation more manageable without compromising thoroughness [33]. This streamlined approach enhances efficiency, enabling quicker assessments crucial for timely decision-making in practical applications. Despite its simplification, it is maintaining the analytical rigor of AHP, making it well-suited for evaluating complex, multi-criteria problems like public transportation sustainability [34]. This tool helps streamline research and provides transparent, actionable insights for sustainability enhancement by focusing on the most critical factors based on expert input. Additionally, combining between it allows for a comparative evaluation, ensuring robust and reliable findings through a comprehensive and validated framework[35].This paper targets bridging the research void by comprehending and ranking influential criteria. The sustainability of public transportation is related to prioritizing the most important influential factors by applying an innovative method. Based on [36], forty-four indicators include the main dimension, which was adopted in this study to investigate the transportation field. The following parts of the paper follow this structure: Section 2 reviews the literature. Section 3 outlines the methods employed in this research. Section 4 presents the findings, and Section 5 delves into the implications and potential directions for future research. Lastly, Section 6 offers the conclusion and an exploration of possible limitations and implications.

2. Literature review

Sustainable transportation has garnered significant attention from academics, policymakers, and industry experts. This is mainly due to its association with sustainable development, encompassing environmental, social, and economic dimensions. Furthermore, the shift toward future mobility is driven by the imperative of achieving economic, environmental, and social sustainability [10]. Globally, there is a noticeable surge in the growth of intermodal transport, driven by the pursuit of heightened transport efficiency and sustainability. This evolving landscape poses challenges for participants in intermodal transport systems, necessitating a thorough analysis of various factors such as human behavior, network planning, geographical considerations, external influences like politics and economics, and transportation modes [37,38]. According to studies, sustainable transportation indicators can be divided into four dimensions: social economics, environment, and technology[36,39]. Four significant issues must be considered for sustainable mobility, including managing environmental comprehensiveness, incorporating casual factors, and linking indicators systems and policy making [40]. Eboli and Mazzulla provide a comprehensive set of performance indicators that objectively measure public transport service quality, highlighting the importance of quantitative and qualitative factors in evaluating transit systems[41]. Assessing the sustainability of public transportation poses challenges for planners and decision-makers, as gathering precise data through time-consuming and labor-intensive questionnaires and surveys proves to be a complex task. Extensive questionnaires discourage survey participants, resulting in lower response rates, and maintaining survey representativeness may rely on high costs or extended survey durations [11].

Sinha and Labi emphasize the critical role of systematic decision-making processes in transportation, particularly integrating project evaluation and programming principles to ensure effective and sustainable transportation solutions[42]. MCDM methods are practical tools for aiding decision-making for prioritization, ranking, and assigning weights to criteria. Within the realm of this techniques, the primary focus for comparison typically revolves around the coherence of assessments, the effectiveness of the survey process concerning response rates, evaluation speed, and the overall quantity of responses, with simplifying the survey process and incorporating consensus-building [27,40,43], employ an MCDM procedure to select the most suitable sustainable mode of transportation, evaluating factors such as travel safety, travel duration, travel comfort, travel expenses, and weather conditions. Among these factors, travel time and cost are most important. The analysis encompasses city bikes, electric kick-scooters, electric scooters, and electric cars, with the findings indicating that city bikes are the top-ranked choice. Another study applied critical elements of this methodology to evaluate various public transportation solutions in a specific 15 km corridor in the center of Wroclaw in Poland. The study concentrated on six alternative scenarios for analysis [44]. When implementing a multi-level criteria decision system, it becomes evident that decision-makers must invest more cognitive effort. The AHP technique, a commonly used method in transportation, was introduced by [45]. Handling intricate multi-criteria scenarios. The method has been utilized in various studies to address transportation challenges like sustainable urban transport development. Employing a fuzzy analytic hierarchy process (FAHP), a business model canvas framework is crafted for public transportation organizations, encompassing impact elements and their external environment [46]. Integrating two MCDM alternatives, Interval-Valued Intuitionistic Fuzzy Analytical Hierarchy Process and Distance-based Assessment (IVIF-AHP & CODAS), ensures consistent, reasonable results and guides future improvements in public transportation service quality [46,47,48], Introduce an AHP-driven method for choosing alternative options in Delhi's eco-friendly transport system. AHP instruments assess the influence of environmentally conscious transport measures, such as mode sharing, multi-modal solutions, and intelligent transport, on urban sustainability [49]. A study employed the (AHP) to establish preference weights among diverse evaluator groups of passengers, company managers, and governmental officers. Using a simplified Saaty scale, the study ensured comparable results and addressed challenges in other AHP applications. The findings presented a priority ranking of supply quality elements, aiding policymakers in synthesizing public transportation aspects for the benefit of the participants [50]. PAHP, introduced by [51], is a novel methodology designed to ease the burden on decision-makers in the Analytic Hierarchy Process by decreasing pairwise comparisons compared to the conventional AHP method. This approach has been applied to various contexts, including social housing project initiatives and user satisfaction surveys on public transport [52]. In another study by [33], the efficiency of PAHP was tested through an experiment involving 100 university students. As part of this research project, students were tasked with assessing the area of various geometric shapes, and the evaluations were conducted using both the traditional AHP and the parsimonious AHP methods. The methodology of the PAHP was initially constructed to unburden the evaluators of an AHP survey from the numerous pairwise comparisons caused by the several alternatives in decision problems [35]. A different study applied PAHP to prioritize the impacts of practical factors on tourists' decision-making process [34].

PAHP presents a potential remedy for the deficiencies observed in

AHP surveys involving the public. It diminishes the cognitive demands within a multi-level decision framework, incorporates consultative elements to eliminate the risk of incomplete assessments, and, in situations where pairwise comparison matrices exhibit unacceptable inconsistency, allows for a dialogue with respondents to adjust their values to meet the 0.1 threshold value for the Consistency Ratio [33,35,53].

PAHP distinguishes itself from traditional AHP and Fuzzy AHP (FAHP) by reducing the number of pairwise comparisons, which minimizes cognitive load and enhances efficiency, making it more time-effective and cost-efficient[54]. While traditional AHP involves extensive comparisons, potentially leading to decision-maker fatigue, PAHP simplifies this process without sacrificing accuracy. Compared to FAHP, which handles uncertainty through complex fuzzy logic, PAHP still ensures consistency in decision-making but with greater ease of application, making it ideal for complex, multi-criteria scenarios like sustainable urban transport[35].

Compared with other MCDM tools, we can see the advantage of using PAHP. [55], The traditional AHP identified crucial indicators like service reliability, safety, and environmental impact, aligning with this study's findings. The PAHP method, however, streamlines the process by minimizing pairwise comparisons, making it more efficient for large or complex assessments without losing accuracy [46]., FAHP method, which accounts for uncertainty in expert judgments, has been used to assess sustainable transportation, emphasizing safety and environmental impact. While FAHP provides robust decision-making, it adds complexity with fuzzy logic. In contrast, the PAHP method in this study offers a more straightforward yet reliable approach to prioritizing sustainability criteria without directly addressing uncertainty. The technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method was used to rank transportation alternatives based on their closeness to an ideal solution, focusing on factors like cost, efficiency, and environmental impact. The findings strongly emphasize operational costs and environmental sustainability, as the PAHP results in this study do. However, TOPSIS, while effective in ranking alternatives, does not provide the same hierarchical structure as PAHP or AHP, which could limit its application when a more detailed criteria analysis is needed [56]. Fuzzy TOPSIS evaluates corporate performance on environmental, social, and governance (ESG) factors, focusing on environmental and social impacts, similar to the PAHP study's emphasis on ecological sustainability indicators like emissions and pollution. However, Fuzzy TOPSIS adds complexity with fuzzy logic, offering nuanced insights but requiring more computational effort [57].. The multi-attribute utility theory (MAUT) method, employed in some studies to evaluate transportation systems, focuses on maximizing utility based on the weighted sum of attributes. [58] used MAUT to assess sustainability performance, emphasizing cost-effectiveness and environmental sustainability, like the PAHP findings. However, MAUT's additive nature may oversimplify the interactions between criteria, whereas PAHP offers a more structured approach to understanding these interactions.

Overall, the literature indicates that while various multi-criteria decision-making (MCDM) methods have been applied to prioritize factors in public transportation, none have employed the PAHP approach extensively to cover all dimensions of public transportation. This study focuses on deploying PAHP in two stages to rank the factors influencing transit decision-making in a detailed manner, encompassing many realistic criteria and offering a more comprehensive evaluation of complex transit systems.

3. Methodology

3.1. Overview

The present study employs the concept of MCDM to address the gaps in evaluating the public transport system. Fig. 1 illustrates the research process for evaluating sustainability indicators in public transportation. It begins with constructing the problem structure, which identifies 44 indicators across four primary dimensions: social (17 indicators), economic (10 indicators), environmental (9 indicators), and technical (8 indicators). PAHP was used in the first survey round to gather responses from 80 experts, including professors, PhD students, consultants, and policymakers. A total of 45 experts provided valid responses, ranking the indicators from 0 to 100. Based on this ranking, the number of indicators was reduced to 14: 3 for social, four for economic, three for environmental, and four for technical.

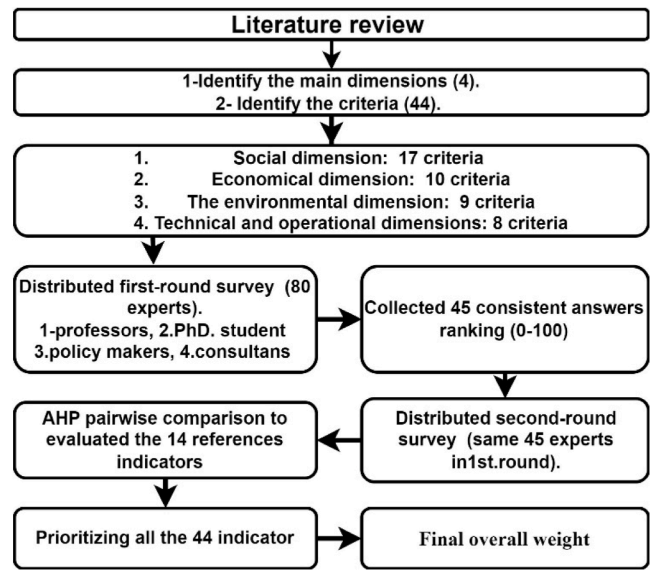

Fig. 1. The methodological framework of the PAHP process.

In the second round, the same group of 45 experts participated in a traditional AHP pairwise comparison survey to further evaluate and prioritize the 14 selected indicators. The experts scored the indicators, and the process concluded by prioritizing these key sustainability indicators in public transportation.

This study organizes the multi-criteria decision-making (MCDM) approach, as shown in Fig. 2. The hierarchy organizes the decision-making process, placing the main goal at the top, the alternatives at the bottom, and the criteria for evaluating these options between the overarching objective and the choices. Because MCDM addresses fundamental attributes, fewer alternatives are typically evaluated; including more options would complicate the prioritization process. The outcome stems from assessing each possible solution against a set of defined criteria [60]. Additionally, the range of feasible solutions may vary widely depending on the priorities set by decision-makers [32]. This research adopts explicitly the AHP method [61] and the PAHP approach introduced by [33]. Public transportation plays a pivotal role in urban mobility, and as cities strive for sustainability, assessing public transport effectiveness becomes crucial. Multiple sustainability indicators must be evaluated systematically, encompassing environmental, social, technical, and economic dimensions. With a clear

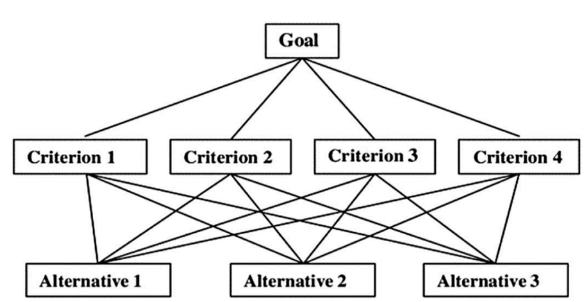

Fig. 2. A standard MCDM hierarchy [59].

understanding of these indicators and their interdependencies, it is easier to formulate effective strategies for improving the sustainability of public transportation. The complexity and interconnectedness of these indicators necessitate using robust Multi-Criteria Decision-Making (MCDM) tools for a comprehensive evaluation [27,35,48].

3.2. The AHP approach

The AHP, a tool within the realm of MCDM, relies on numeric ratings to ascertain the significance of defined indicators. Fig. 2 illustrates a hierarchy structure of the AHP issue, with the primary goal at the pinnacle and the choices at the base. Criteria assessing alternatives stand between the overarching objective and the options, as outlined by [61]. The AHP technique requires pairwise judgments and matrix algebra to determine the importance of criteria. While valuable for complex decisions, AHP has limitations. The implementation steps of pure AHP, per Saaty, are outlined as follows:

I. Initially, the problem is outlined, and a specific objective is established.
II. Subsequently, a hierarchical structure is established, progressing from the highest level (i.e., the objective) through the intermediary level (i.e., indicator." C_j") to the lowest level (typically denoted by the alternative “A”).
III. A commonly employed nine-level numerical scale assigns quantitative importance to each criterion (see Table 1). The process involves assessing pairwise comparison matrices that measure indicators and alternatives concerning the objective. Consequently, matrix M ($n \times n$) is formulated based on the number of options A (Eq. (1)), incorporating values C_{ij}, Where I depict the foundational comparative indicator linked to row, and I and j indicate the criterion being compared to i.

$$M = \begin{bmatrix} 1 & C_{12} \cdots & C_{1n} \\ \vdots & \ddots \cdots & \vdots \\ \frac{1}{C_{1n}} & \frac{1}{C_{2n}} \cdots & 1 \end{bmatrix} \quad (1)$$

Eq. (2) Restructures matrix M using a reciprocal matrix where.$C_{ij} = \frac{1}{C_{ij}}$

$$M = \begin{bmatrix} 1 & C_{12} \cdots & C_{1n} \\ \vdots & \ddots \cdots & \vdots \\ \frac{1}{C_{1n}} & \frac{1}{C_{2n}} \cdots & 1 \end{bmatrix} \begin{bmatrix} W1 \\ W2 \end{bmatrix} = \lambda\max \begin{bmatrix} W1 \\ W2 \end{bmatrix} \quad (2)$$

The eigenvector is computed using Eq. (3) to obtain the weight of the criteria.

$$MW = \lambda_{\max} W \quad (3)$$

After completing pairwise comparisons and obtaining criteria weights, consistency evaluation involves computing the consistency index (CI) through eigenvalue computations. λmaxAs follows:

$$CI = (\lambda_{\max} - n)/(n-1) \quad (4)$$

With n representing the matrix size, CI’s consistency ratio (CR) is used to gauge decision consistency. A CR below 0.10 shows acceptable consistency. However, if the CR exceeds 0.10, it suggests bias in the judgment matrix. Assessments should be reviewed and refined to create a consistent matrix. The CR can be calculated using the following formula:

$$CR = CI / RI \quad (5)$$

Here, RI represents mean random consistency, and the specific values of RI can be extracted from Table 2.

AHP surveys encompass a multitude of decision-makers and evaluators. Consequently, the individual assessments must be consolidated using the geometric mean, as demonstrated in the following formula.

Equation:

$$FM = \left[\sqrt[r]{\prod_{d=}^{r} e_{ijk}} \right] i,j = 1, \ldots \quad (6)$$

3.3. The PAHP approach

The fundamental aim of the PAHP method is to minimize the number of inquiries posed in a survey and circumvent extensive pairwise comparisons. (PAHP) was chosen over other Multi-Criteria Decision-Making (MCDM) methods due to its ability to streamline the decision-making process by reducing the number of pairwise comparisons required. This makes PAHP particularly efficient and less cognitively demanding for experts while still providing robust and reliable prioritization of criteria. Unlike traditional AHP alone, which can become cumbersome with large datasets, PAHP maintains accuracy and consistency in results while improving practicality, especially in complex scenarios involving multiple sustainability indicators[53]. The subsequent steps of the PAHP methodology, as introduced by[51], are detailed below.

1. A direct assessment uses a designated scale (e.g., 0–100) to evaluate the indicators Cj concerning alternative A. Consequently, the normalization process is applied to all criteria. The normalized values for the requirements are represented by λj for all $j = 1 \ldots n$ and for all $t = 1 \ldots n$. These normalized indicators are then organized in an ascending order, allowing for the calculation of new ratings based on the normalized values for all indicators. These updated scores are denoted as r_j.
2. The reference point indicator (C_r) is chosen according to its new ranking within the Cj criteria. The specific count of based indicators denoted as t is determined by the total number of indicators, as illustrated in Table 3.
3. With the designated number of indicators, t, the AHP above pairwise comparison procedures are carried out, yielding the normalized AHP values for the Cr indicators. These AHP scores are denoted as u(Cj). The respective ratings confirm the monotonic nature is upheld, ensuring that where $D(r_{j1}) > D(r_{j2})$ if u $C_{r1} \geq C_{r2}$
4. The scores for the remaining indicators, denoted as $u(r_j)$ (comprising all criteria except the references criteria), are determined through linear interpolation using the following[62]:

$$Open(r_j) = u(C_j) + \frac{u(C_{j+1}) - u(C_J)}{\lambda_{j+1} - \lambda_j} \times D(r_j) - D(C_j) \quad (7)$$

Table 1
The AHP preference’s pairwise comparison ranking [59].

Definition	Score
Extreme importance	9
Very strong importance	7
Strong importance	5
Moderate significance	3
Equal importance	1
Balancing the mentioned values	2, 4, 6, and 8

Table 2
Random consistency values (RI) for the different sizes (n) [59].

N	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41

Table 3
The minimum indicators count C_j with the given indicator number [33].

Reference indicators C_r	3	4	5	6	7	8	9
indicators C_j	7	10	14	19	25	32	40

4. Results

4.1. The weights of the indicators

Fig. 4. illustrates four dimensions to evaluate sustainability (social, economic, environmental, and technical) as the main criteria. Then, 44 sub-criteria were distributed as follows: 17 for the social aspects,10 for an economic field, 9 for environmental, and eight sub-criteria for the technical aspects. Hence, criteria receive direct assessments. Next, normalization to 1 is done for all requirements—Table 4 displays normalized indicator results, ordered in ascending sequence.

According to Table 3, fourteen reference criteria are selected as follows:

i. Social (travel time (i.e., the indicator with the highest rank), health (i.e., the indicator with the middle- rank), and gender (i.e., the indicator with the lowest rank).
ii. Economical (ticket Price (monthly & daily) (i.e., the indicator with the highest rank), economic efficiency, income average (i.e., the indicator with the middle- rank), and Environmental taxes (i.e., the indicator with the lowest rank).
iii. Environmental (emissions (i.e., the indicator with the highest rank), bus age (i.e., The indicator with the middle- rank), and consumption of land use (i.e., the lowest ranking indicator).
iv. Technical (traffic (i.e., the highest-ranking indicator), climate change (i.e., middle-ranking indicator), and depreciation (i.e. the lowest ranking indicator).

Table 4
The direct evaluation and the normalized values of the indicators.

indicators	Normalization value λ(C)	indicator	Normalization value λ(C)
Social criteria		Economic criteria	
Travel time	8.95	Ticket Price	7.72
Security	8.18	Cost operation	6.89
Accessibility	8.07	Travel cost	6.35
Waiting time	7.47	Travel distance	6.34
Reliability	7.09	*Av.* income	5.94
Affordability	6.9	Economic efficiency	5.93
Vehicle occupancy rate	6.14	Capital cost	4.71
Equity	5.85	GDP	4.41
Health	5.19	Pricing mechanisms	3.99
Age	4.91	Environment taxes	3.92
Loyalty	4.78		
date of journey	4.57		
Family size	4.4		
Type of journey	4.36		
Employment	4.02		
Education	3.21		
Gender	3.06		
Environmental criteria		Technical criteria	
Emissions	7.29	Traffic	8.4
Congestion	7.11	LOS	7.63
Population	6.97	Infrastructure	7.05
Pollution	6.71	Technology solutions	6.72
Climate change	6.41	Buses Age	4.77
Fuel consumed	4.96	battery capacity	3.81
Energy consumption	4.94	Self-regulation	3.68
Noise	4.06	Depreciation	3.51
Land use (consumption)	2.88		

The second survey phase involves based indicators and applying pairwise comparison matrices to implement the AHP method. The results of the second survey are presented in Table 5.

The CR values are below 10 %. Ultimately, linear interpolation is applied (Eq. (7)) to obtain the final values for the remaining indicators, as follows:

4.1.1. Social calculation

According to Eq. (7), the final PAHP weight for social creation is calculated based on the reference criteria in Table 6.

4.1.2. Economical calculations

Refer to Eq. (7); the final PAHP weight for economic creation is calculated based on the reference criteria in Table 7.

4.1.3. Environmental calculations

The final PAHP weight for economic indicators is calculated based on the reference criteria in Table 8 And Eq. (7).

4.1.4. Technical calculations

Refer to Eq. (7); the final PAHP weight for technical creation is calculated based on the reference criteria in Table 9.

According to Fig. 3, the final overall weight of all indicators, the summary for prioritizing sustainability criterion will be as follows: the highest indicator ticket prices with 0.048, followed by emissions with 0.046, 0.044 for congestion, 0.042 for Population, 0.041 for cost operation, travel distance, travel cost and traffic get the same importance with 0.036 and in the tenth stage the climate change with 0.034.

Pareto chart analysis in Fig. 4 illustrates the prioritization of sustainability indicators in public transportation, highlighting ticket price as the most critical factor, followed by emissions, congestion, population, and cost operation, which account for a significant portion of the cumulative weight. This indicates that affordability, environmental concerns, and operational efficiency are paramount for achieving sustainability in public transportation systems. The steep cumulative curve emphasizes that many high-priority factors dominate the sustainability assessment, aligning with the Pareto principle, where around 20 % of factors contribute to 80 % of the impact. Lower-weight indicators, such as gender, education, and depreciation, while less influential, underline

Table 5
The scores of the based indicators(reference).

Indicators	value u(Cr)	Ranking
Social based indicators		
Travel time	0.4911	1
Health	0.4196	2
Gender	0.0856	3
Economic based indicators		
Ticket Price (daily & monthly)	0.3863	1
Av. Income	0.2674	2
Economic efficiency	0.2448	3
Environment taxes	0.103	4
Environmental based indicators		
Emissions	0.5104	1
Climate change	0.3733	2
Land use(consumption)	0.1148	3
Technical based indicators		
Traffic	0.49	1
Technology solutions	0.267	2
Buses Age	0.1537	3
Depreciation	0.0885	4

Table 6
The final overall weight of the social indicators.

Indicators	Ranking	Final PAHP weight	Final overall weight
Travel time	1	0.491	0.0234
Security	2	0.476	0.0227
Accessibility	3	0.474	0.0226
Waiting time	4	0.463	0.0221
Reliability	5	0.456	0.0217
Affordability	6	0.452	0.0215
Vehicle occupancy rate	7	0.438	0.0208
Equity	8	0.432	0.0206
Health	9	0.42	0.02
Age	10	0.376	0.0179
Loyalty	11	0.355	0.0169
date of journey	12	0.322	0.0154
Family size	13	0.296	0.0141
Type of journey	14	0.289	0.0138
Employment	15	0.236	0.0112
Education	16	0.109	0.0052
Gender	17	0.086	0.0041

Table 7
The final overall weight of the economic indicators is as follows.

Indicators	Ranking	Final PAHP weight	Final overall weight
Ticket Price (monthly & daily)	1	0.386	0.048
cost operation	2	0.331	0.041
travel cost	3	0.294	0.036
Travel distance	4	0.295	0.036
Av. income	5	0.267	0.033
economic efficiency	6	0.245	0.03
capital cost	7	0.158	0.02
GDP	8	0.138	0.017
pricing mechanisms	9	0.103	0.013
Environment taxes	10	0.108	0.013

Table 8
The final overall weight of the environmental indicators.

Indicators	Ranking	Final PAHP weight	Final overall weight
Emissions	1	0.51	0.046
Congestion	2	0.482	0.044
Population	3	0.461	0.042
Pollution	4	0.42	0.038
Climate change	5	0.373	0.034
Fuel consumed	6	0.266	0.024
Energy consumption	7	0.267	0.024
Noise	8	0.201	0.018
Land use(consumption)	9	0.115	0.01

Table 9
The final overall weight of the technical indicators.

Indicators	Ranking	Final weight	Final overall weight
Traffic	1	0.49	0.036
LOS	2	0.388	0.028
Infrastructure	3	0.311	0.023
Technology solutions	4	0.267	0.02
Buses Age	5	0.154	0.011
battery capacity	6	0.104	0.008
Self-regulation	7	0.097	0.007
depreciation	8	0.089	0.006

the importance of inclusivity and long-term planning in a comprehensive sustainability framework. These findings align with existing literature emphasizing affordability and environmental considerations as key drivers while validating the PAHP methodology's ability to streamline complex decision-making. Policymakers should focus on top-ranked indicators, such as affordable pricing and emissions reduction, to maximize immediate impact while gradually addressing lower-priority factors to ensure holistic and inclusive development. This prioritization provides actionable insights for crafting targeted strategies to enhance the sustainability of public transportation systems.

5. Discussion

The findings of this study prioritize the sustainability criteria for public transportation across social, economic, environmental, and technical dimensions. While these results provide valuable insights, they gain greater significance when contextualized within the existing literature. The study employed a two-stage evaluation process: 45 experts assessed and scored each sub-criterion in the first round. Subsequently, using PAHP techniques, reference criteria were selected. In the second round, the same group of experts conducted pairwise evaluations of these reference criteria, allowing for the calculation of AHP and final AHP weights for all sub-criteria within each dimension.

•Social Dimension

Travel time emerged as the most influential indicator within the social dimension (weight: 0.491), consistent with prior studies emphasizing its pivotal role in shaping sustainable public transportation systems [63]. For example, Esztergár-Kiss et al. [64]highlight travel time as a determinant of mode choice, which aligns with our findings. Furthermore, our study extends this understanding by quantitatively ranking other critical factors, such as reliability (weight: 0.456) and affordability (weight: 0.438), highlighting their nuanced contributions to overall sustainability. Unlike studies focusing solely on isolated factors [65], our approach integrates these indicators into a comprehensive framework, enabling policymakers to prioritize interventions effectively.

Equity and health, with weights of 0.432 and 0.420, respectively, reinforce the importance of public transportation for addressing broader social challenges, such as accessibility and public health. These results align with prior research [50,53], emphasizing the need for inclusive and health-conscious transportation policies. By ranking these indicators, this study complements existing literature by providing a structured methodology for their prioritization.

•Economic Dimension

The study identifies ticket prices as the most critical economic indicator (weight: 0.386), consistent with global trends emphasizing affordability as a driver of public transportation demand [27,33]. This finding corroborates Kumar et al. [66], who highlighted the importance of balancing affordability and operational sustainability. Moreover, the weights assigned to operational costs (travel cost: 0.295, cost of operation: 0.331) underscore the dual necessity of maintaining financial efficiency while keeping transportation accessible to diverse income groups. Compared to previous studies focusing on singular economic metrics [28,49], our results provide a multi-faceted prioritization, offering actionable insights for economic planning.

Including environmental taxes (weight: 0.103) as a lower-ranked economic factor reflects an emerging but less immediate focus on fiscal policies to incentivize sustainable practices. This contrasts with findings by Awasthi and Chauhan [49], who emphasized environmental taxes as a critical factor, indicating a potential gap between theoretical frameworks and practical applications in public transportation systems.

•Environmental Dimension

Emissions (weight: 0.510) and pollution (weight: 0.420) are the most significant environmental indicators, aligning with global priorities to mitigate climate change and improve air quality [23,46]. These findings resonate with Yoon et al. [13], who underscore the environmental impact of transportation and reinforce the need for eco-friendly policies. Notably, our study adds depth by quantitatively demonstrating the relative importance of emissions over other environmental factors, such as energy consumption (weight: 0.266) and noise (weight: 0.201).

The prioritization of climate change (weight: 0.373) reflects its

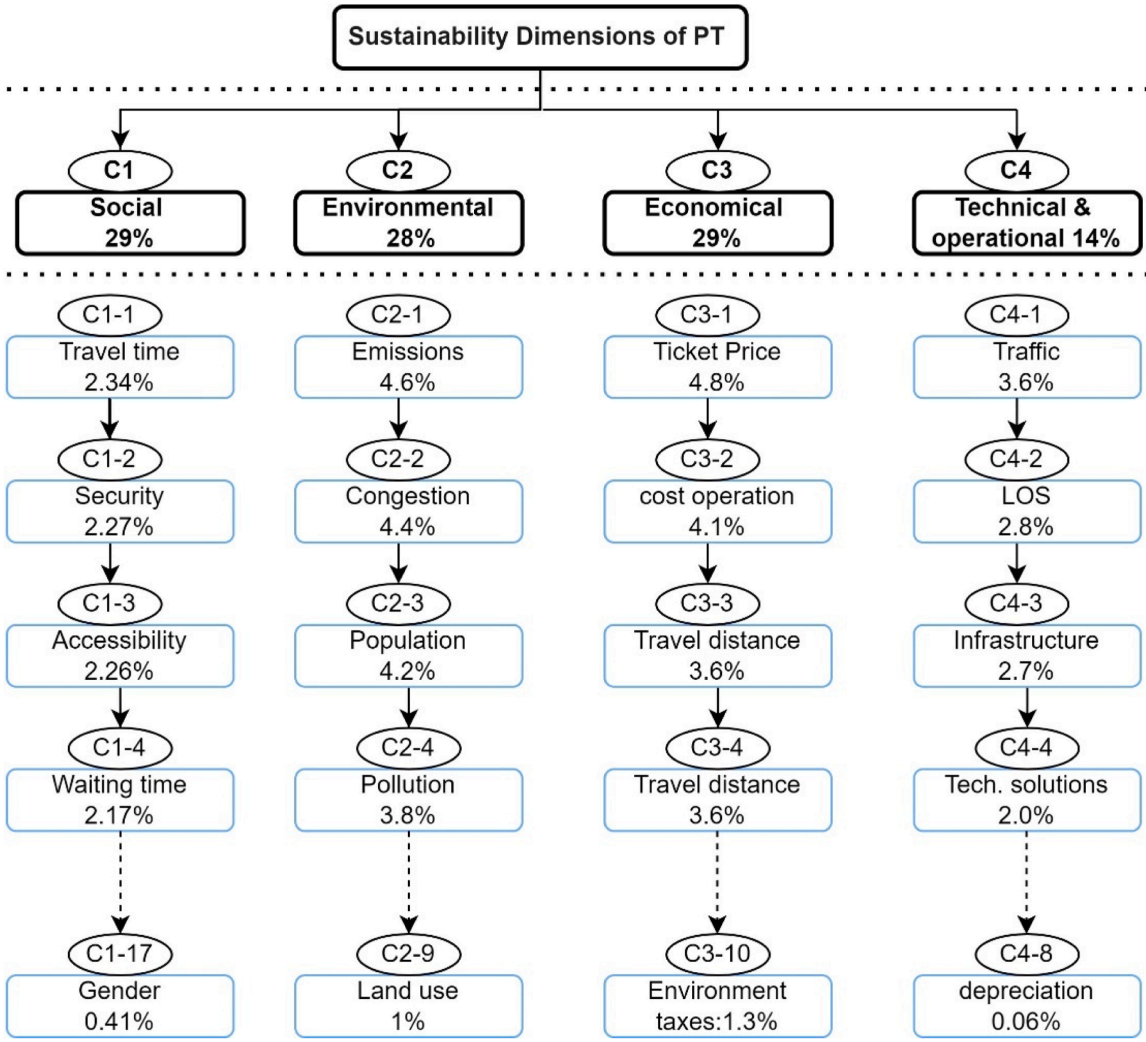

Fig. 3. Frequency of Final overall weight creation.

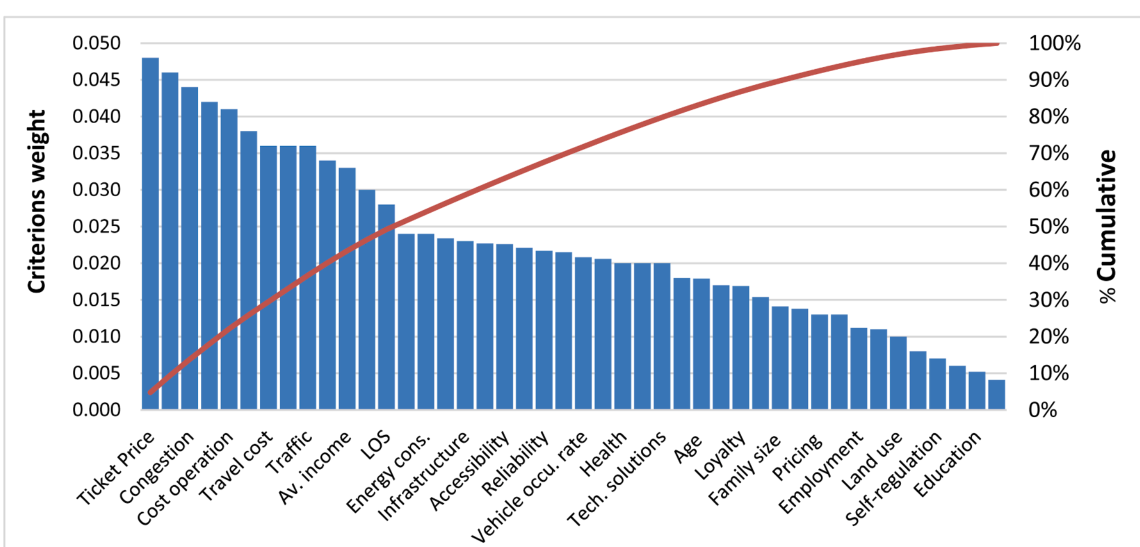

Fig. 4. Pareto analysis for sustainability criteria.

global significance, consistent with studies that integrate transportation strategies into broader climate action plans [4,67]. However, the relatively lower weight assigned to land use consumption (weight: 0.115) suggests that its immediate impact may be context-specific, warranting further investigation into regional variations. This nuanced understanding of environmental indicators advances the existing body of knowledge by integrating them into a hierarchical framework, facilitating targeted interventions.

•Technical Dimension

In the technical dimension, traffic management (weight: 0.490) and Level of Service (LOS) (weight: 0.388) are prioritized, underscoring their operational importance. These findings align with Duleba et al. [50]., who identified traffic management as a critical determinant of service quality. By quantitatively ranking these indicators, our study offers a systematic approach to addressing technical challenges, bridging the gap between academic research and practical applications.

While indicators like buses' age (weight: 0.154) and depreciation (weight: 0.089) are ranked lower, they highlight the importance of long-term infrastructure planning. This aligns with findings by Abastante et al. [33], who advocate for integrating lifecycle considerations into transportation planning. Compared to studies focusing solely on immediate technical factors[45], our research emphasizes a balanced approach, incorporating operational efficiency and infrastructure sustainability.

This study's integration of the PAHP methodology into the sustainability assessment of public transportation offers a novel contribution to the literature. Unlike traditional AHP approaches, which are often constrained by cognitive demands and scalability issues [54], the PAHP method streamlines the decision-making process without compromising analytical rigor. By incorporating direct assessments and pairwise comparisons, our study bridges gaps identified in prior research [34], offering a robust framework for prioritizing sustainability indicators.

The findings also validate and extend existing frameworks, such as those proposed by Kumar et al. [66]and Duleba et al. [50], by quantitatively ranking indicators across four dimensions. This comprehensive approach not only corroborates prior studies but also provides actionable insights for policymakers, addressing the multidimensional challenges of sustainability.

By linking our findings to existing literature, this study underscores the interconnectedness of social, economic, environmental, and technical dimensions in public transportation sustainability. The PAHP methodology enhances our understanding of these relationships, offering a structured and efficient approach to prioritization. These insights contribute to the broader academic discourse and provide a practical roadmap for policymakers aiming to achieve sustainable urban mobility.

5.1. Policy implications

Considering expert evaluations and PAHP weight calculations, a comprehensive set of policy implications emerges, emphasizing the imperative for an integrated approach to enhance public transportation sustainability. These interconnected policies aim to create a harmonized system addressing various dimensions crucial for success:

To ensure inclusivity and accessibility, prioritize policies that make public transportation user-friendly for diverse demographic groups. This involves tailoring infrastructure and services to cater to varying abilities and age groups. Optimizing travel times and minimizing waiting times are central to policies that attract and retain passengers, ultimately bolstering the competitiveness of public transportation. Incorporate pricing mechanisms that account for the environmental impact of transportation choices. This encourages sustainable practices and aligns with broader ecological goals. Efficient capital investment management is vital. Policies should balance generating revenue and maintaining accessible ticket prices across diverse income levels. Integrate advanced technologies into public transportation to enhance efficiency, reduce operational costs, and contribute to overall economic sustainability. Implement flexible ticket pricing structures responsive to economic changes, ensuring affordability for passengers while supporting financial sustainability. Environmental considerations must be integrated into urban planning. Align transportation strategies with broader ecological goals to create sustainable, eco-friendly urban environments. Manage population growth and alleviate congestion through efficient transportation systems, contributing to sustainable urban development. Prioritize sustainable land development practices to prevent environmental degradation, ensuring transportation infrastructure aligns with broader ecological goals. Invest in the development and maintenance of resilient transportation infrastructure. Governments and authorities should prioritize well-designed structures to ensure reliability and longevity. These policies collectively form a holistic strategy for public transportation sustainability, addressing the social, economic, environmental, and technical dimensions. By adopting these measures, policymakers can foster a comprehensive and integrated approach that enhances the overall sustainability of public transportation systems, meeting the diverse needs of communities while promoting a resilient and environmentally conscious urban landscape.

6. Conclusion

This study meticulously examined and prioritized factors influencing the sustainability of public transportation across four critical dimensions: social, economic, environmental, and technical. We were conducted through a robust methodology involving expert evaluations and the innovative PAHP technique. The study executes two survey rounds involving the same specialist group to evaluate the criteria. However, the second survey involves a reduced number of criteria. By integrating direct evaluations and pairwise comparisons of based indicators, the research derives final values for all the indicators. These outcomes form the basis for analyzing and prioritizing public transportation sustainability criteria.

Our research aimed to unravel the intricacies of sustainable public transportation by prioritizing factors within critical dimensions. Through the innovative application of the PAHP technique, we distilled insights from expert evaluations, offering a nuanced understanding of the factors shaping sustainability. The final scores and the prioritizing results for all criteria are acquired. Drawing conclusions based on the outcomes can be stated as follows:

- Social Dimension: Travel time is the highly impactful indicator with a 0.491 importance weight, which is followed by security with 0.476, Accessibility with 0.474, and Waiting time with 0.463, as sensitivity emerged as a pivotal factor in shaping the socio-economic landscape of public transportation and highlighted as crucial, reflecting the broader economic health of the community.
- The least significant criterion impacting the selected gender was 0.086. Equity and health get close weights of 0.432 and 0.420, which refer to the importance of the availability of public transport for most people without any restriction; providing public health requirements in these modes will have a positive role in increasing the demand for public transportation.
- Economic Dimension: Ticket prices (weight: 0.386), economic efficiency (weight: 0.245), and operational costs (travel cost weight: 0.295, cost of operation weight: 0.331) were identified as critical economic factors. These underscored the importance of financial sustainability and efficiency in public transportation operations.
- Environmental Dimension: Environmental considerations, weighing 0.281, emphasized the need to mitigate ecological impact and promote sustainable practices. Emissions (weight: 0.510) and pollution (weight: 0.420) emerged as top concerns, signaling the urgency for eco-friendly policies in public transportation planning.

- Technical Dimension: In the technical realm, Level of Service (LOS) and Traffic stood out as top priorities, with weights of 0.388 and 0.490, respectively. These underscored the crucial role of efficient operational performance and traffic management in enhancing the sustainability of public transportation systems.
- These criteria should be the focal point of policy initiatives and strategic planning efforts. Indicating the interconnectedness of environmental impact and urban planning with the overall success of public transportation.
- AHP is a valuable tool for sustainability assessment with potential for broader application in sectors like energy, water management, and urban planning. Future research could further validate its versatility and enhance comprehensive sustainability strategies across various domains.

This study confronts certain limitations that warrant consideration. as follows:

- **Oversimplification:** PAHP's reduction of pairwise comparisons might oversimplify complex sustainability issues, potentially missing essential interactions between criteria.
- **Expert Bias:** Reliance on expert judgments in PAHP may introduce biases, notably if the specialist group lacks diversity, leading to skewed results**.**
- **Limited Handling of Uncertainty:** PAHP does not inherently account for uncertainty in decision-making. The method assumes that experts can provide precise evaluations; this limitation could affect the robustness of the results, particularly in dynamic and complex environments like public transportation planning.
- Integrating More Comprehensive Criteria: Expanding the criteria considered in the PAHP analysis could help capture a broader spectrum of factors influencing sustainability. Future studies could investigate how adding additional criteria might affect the overall results, ensuring that more complex interactions are adequately represented.
- The PAHP method is its assumption of independent criteria, which overlooks the interdependencies often present in public transportation sustainability, suggesting the need for more advanced techniques like the Analytic Network Process (ANP) for a more comprehensive evaluation.
- Incorporating Methods to Handle Uncertainty: To enhance the robustness of the PAHP method, future research could explore integrating approaches that explicitly account for uncertainty. Combining PAHP with fuzzy logic or probabilistic models might offer a more nuanced understanding of sustainability indicators, particularly in environments where data is uncertain or incomplete.
- Expanding the Scope to Other Sectors: While this study focuses on public transportation, the broader applicability of the PAHP methodology to other areas of sustainability assessment is promising. Future research could apply PAHP to other sectors, such as energy, water management, or urban planning, to evaluate its effectiveness in different contexts and identify sector-specific sustainability indicators. This could validate the methodology's versatility and contribute to a more comprehensive approach to sustainability assessments across various domains.

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the authors used ChatGPT-Open AI 4.0 to improve the language of this research. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

CRediT authorship contribution statement

Ammar Al-lami: Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Ádám Török:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and materials used to support the findings of this study are available from the corresponding author upon reasonable request.

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