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Integrating Analytic Hierarchy Process and Parsimonious Preference Information for Socio-Economic Sustainability Assessment in Urban Public Transport

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ABSTRACT

This study integrates the Analytic Hierarchy Process (AHP) and Parsimonious Preference Information to present a structured multi-criteria decision-making (MCDM) framework for assessing the socio-economic sustainability of public transport systems. Despite extensive research on technical and environmental transport performance, few studies have systematically prioritised socio-economic indicators using expert-based MCDM approaches. This study addresses this gap through a survey of 45 transport experts representing academia, policy, and operations. To determine their relative importance, a total of 21 indicators were first evaluated and normalised. The three most important variables affecting user satisfaction and system effectiveness were found to be Affordability (0.0645), Reliability (0.0625), and Accessibility (0.0621). In contrast, Education Level (0.0147) and Gender (0.0102) were the least prioritised. Pairwise comparisons between representative indicators were performed using the PAHP approach, which was verified by consistency ratio tests. This resulted in reliable final weightings by linear interpolation. The results show a strong emphasis on operational and economic criteria, suggesting potential gaps in stakeholder viewpoints and the need for more inclusive assessment frameworks. The results provide policymakers with practical advice on how to prioritise affordability-focused and user-centred service enhancements in order to increase the social sustainability of urban transport. Future research should incorporate environmental and technical sustainability aspects to develop a thorough evaluation model and address the study's expert-centric scope, context-specificity, and lack of behavioural data.

1. Introduction

Sustainable urban mobility is a cornerstone of modern city planning, and public transit is essential for enhancing social well-being, lowering environmental impact, and stimulating economic growth. The need for effective, accessible, and inclusive public transport networks grows as urbanisation picks up speed and transportation demand rise. While traditional evaluations of transport

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sustainability have largely concentrated on environmental performance metrics, the social and economic dimensions—including accessibility, affordability, equity, safety, user satisfaction, operational cost, employment, and health impacts—have often been comparatively underexplored. Addressing these dimensions is crucial for achieving a balanced understanding of sustainability that reflects both user needs and system equity. Accordingly, this study focuses on the socio-economic aspects of public transport sustainability, while recognising that future research should integrate these social and economic insights with environmental and technical factors to form a more holistic and comprehensive sustainability framework.

The socio-economic dimension is critical in evaluating public transport sustainability because it directly affects accessibility, equity, safety, and user satisfaction, determining a transit system's effectiveness and inclusivity [1], [2]. The social dimension interrelates with the economic dimension by influencing ridership demand, affordability, and operational efficiency, ensuring financial sustainability [3]. Socio-economic factors also connect with the environmental dimension, as improved accessibility and affordability encourage public transport use, reducing emissions and congestion [4]. Additionally, it aligns with the technical dimension, where infrastructure, service reliability, and technology advancements enhance user experience and equity [5]. A well-balanced socio-economic dimension ensures sustainable urban mobility, making public transport more efficient, inclusive, and environmentally responsible [6].

Despite growing recognition of the importance of social sustainability, existing frameworks often lack a systematic approach to prioritising and integrating these indicators into decision-making processes. Multi-criteria decision-making (MCDM) methods, such as AHP, have been widely used to address complex sustainability challenges. However, these methods can be computationally intensive and cognitively demanding, limiting their practical applicability in real-world scenarios [7].

This study addresses these gaps by introducing a hybrid MCDM approach that combines PAHP with AHP, offering a streamlined and efficient methodology for evaluating socio-economic sustainability in public transport. PAHP and AHP were chosen for their ability to prioritise complex criteria while maintaining analytical rigour efficiently. AHP provides a structured pairwise comparison framework, ensuring logical consistency in ranking sustainability indicators. However, AHP can become computationally intensive with many criteria, so PAHP was integrated to streamline comparisons, reducing cognitive burden while preserving accuracy. Compared to other MCDM methods like TOPSIS or FAHP, PAHP minimises complexity without sacrificing decision quality, making it ideal for handling large datasets and expert-driven evaluations [8]. This combination enhances robustness, efficiency, and practical applicability, ensuring clear, data-driven insights for policymakers by integrating expert-driven assessments.

The primary objective of this research is to identify and prioritise key socio-economic sustainability indicators in public transport using a robust, expert-driven framework. The 21 socio-economic indicators were identified through a comprehensive literature review and expert consultation, ensuring relevance to public transport sustainability. By engaging 80 specialists from academia, consultancy, and policymaking, the study employs a two-phase survey process to reduce cognitive load while maintaining analytical rigour. The first phase utilises PAHP to filter and rank 21 socio-economic indicators, while the second phase applies AHP for pairwise comparisons of the top 14 indicators, yielding a final prioritisation that highlights the most influential factors. The final ranking, derived through linear interpolation, provides actionable insights for urban planners and policymakers.

This study makes several key contributions to the field of sustainable urban mobility. First, it bridges the gap between theoretical frameworks and practical applications by offering a scalable and adaptable methodology for prioritising socio-economic sustainability indicators. Second, it highlights the critical role of travel time, security, accessibility, cost of operation, and economic efficiency in shaping public transport systems, providing evidence-based recommendations for optimising infrastructure investments and operational strategies. Finally, the research underscores the importance of integrating socio-economic equity into transport planning, ensuring that public transport systems meet the diverse needs of urban populations.

The prioritised indicators provide a clear roadmap for enhancing public transport by focusing on efficiency, safety, accessibility, affordability, and financial sustainability. Policies should prioritise reducing travel time through optimised routes, better scheduling, and real-time tracking [9]. Security improvements, such as better surveillance and well-lit stations, can enhance user confidence [10]. Affordable pricing strategies and subsidies can improve accessibility for lower-income groups [11]. Infrastructure and service reliability investments can minimise waiting times and ensure equitable access [12]. Additionally, cost-effective operations and economic efficiency measures, such as dynamic pricing and value-capture financing, can enhance financial sustainability [13]. Integrating health-conscious designs, such as cleaner air standards and ergonomic seating, can enhance passenger well-being integrating health-conscious designs, such as cleaner air standards and ergonomic seating, can enhance passenger well-being [14]. These insights support data-driven transport planning for sustainable, inclusive, and efficient mobility systems.

The remainder of this paper is structured as follows: Section 2 reviews the literature on public transport sustainability and MCDM approaches. Section 3 details the research methodology, including the PAHP and AHP frameworks. Section 4 presents the results, followed by a discussion in Section 5. Finally, Section 6 concludes with key insights, policy implications, and future research directions.

2. Literature Review

Public transport sustainability has become a central focus in urban planning and transportation research, driven by the need to address the interconnected challenges of urbanisation, environmental degradation, and social equity [15]. While the environmental, economic and social dimensions of sustainability have been extensively studied as separate dimensions, the socio-economic dimension remains underexplored despite its critical role in shaping the inclusivity and effectiveness of public transport systems. Social and economic sustainability in public transport encompasses a wide range of indicators, including accessibility, affordability, safety, equity, user satisfaction, cost of operation and economic efficiency, all of which directly influence the quality of life for urban residents and the overall success of mobility systems [16].

2.1 Social Sustainability in Public Transport

The concept of social sustainability in public transport has gained traction in recent years, with researchers emphasising its importance in creating equitable and inclusive urban mobility systems. Litman defines social sustainability as the ability of a transport system to meet the needs of all users, regardless of age, gender, income, or physical ability [17]. Key indicators include accessibility, which ensures that transport services are available to all population groups; affordability, which relates to the cost of using public transport relative to users' income levels; and safety, which directly impacts user confidence and satisfaction [18]. Other critical factors include equity, which addresses the fair distribution of transport resources, and user satisfaction, which reflects the overall quality of the transport experience [19].

Studies have shown that socially sustainable public transport systems contribute to broader urban development goals, such as reducing poverty, improving public health, and fostering social cohesion. For example, affordable and accessible public transport plays a crucial role in enabling low-income populations to access employment, education, and healthcare services [20]. Similarly, ensuring safety and security is essential for promoting public transport use, especially among vulnerable populations, including women and the elderly [21].

Recent research highlights the importance of integrating social and infrastructural dimensions into sustainable urban mobility planning. The availability and quality of sidewalks and bike lanes in nearby areas, along with proximity to popular destinations, emerge as the most influential criteria, while demographic factors are less significant [22]. These findings emphasise that well-designed infrastructure and accessibility play a central role in sustainable mobility, supporting the need for user-centred frameworks such as the one proposed in this study.

Despite the growing recognition of social sustainability, existing frameworks often lack a systematic approach to prioritising and integrating these indicators into decision-making processes. This gap is particularly evident in the context of Multi-Criteria Decision-Making (MCDM), where traditional methods such as AHP and TOPSIS have been criticised for their computational complexity and reliance on expert judgment [23].

2.2 Economic Criteria in Public Transport Sustainability

In addition to promoting urban and regional economic development, economic sustainability guarantees that public transport systems can operate effectively, generate sufficient revenue, and offer affordable services. A thorough grasp of the various elements influencing the financial sustainability, operational effectiveness, and overall economic impact of transportation systems is necessary for evaluating economic sustainability in public transport [24]. Therefore, the notion of economic sustainability in public transport has attracted substantial attention in recent years as policymakers and researchers understand its vital role in guaranteeing the long-term viability and efficiency of urban transportation networks. Economic sustainability is defined as the ability of a transportation system to function efficiently, produce adequate income, and deliver affordable services while contributing to broader economic growth [25]. Cost-effectiveness, which guarantees that services are provided at the lowest possible cost without sacrificing quality; financial viability, which pertains to the system's capacity to pay for capital and operating costs; and economic efficiency, which represents the best possible use of resources to produce the best results, are important indicators [26]. Economic impact, which gauges the system's contribution to job creation, productivity, and urban growth, and fare affordability, which guarantees that services are available to all income groups, are additional crucial considerations [2].

The economically viable public transport systems support more general urban and regional development objectives, including lowering traffic, enhancing air quality, and stimulating economic expansion. In addition, effective public transport enhances labour market connectivity by providing workers with greater access to employment opportunities and expanding consumer markets for businesses [27].

Even while economic sustainability is becoming more widely acknowledged, current frameworks frequently do not prioritise or incorporate these indicators into decision-making processes in a methodical manner, because the financial planning process is further complicated by the substantial upfront investments needed to make the switch to sustainable transportation options, such as electric buses and driverless cars [28].

2.3 Socio-economic Criteria in Public Transport Sustainability

The evaluation of socio-economic sustainability in public transport requires a comprehensive understanding of the diverse factors that influence user experience, system effectiveness, and financial viability [29]. Below, we discuss the key socio-economic criteria identified in the literature. By integrating these socio-economic criteria into decision-making processes, policymakers and urban planners can design public transport systems that are not only socially inclusive but also economically sustainable. This holistic approach ensures that public transport contributes to broader urban development goals, such as reducing poverty, improving public health, and fostering economic growth [30].

i. Affordability

Affordability is a critical factor in ensuring equitable access to public transport, particularly for low-income populations. Affordable fares and subsidised programs can make public transport more accessible and reduce reliance on private vehicles [11]. Studies have shown that affordability directly influences ridership levels and contributes to social equity in urban mobility [31].

ii. Reliability

Reliability refers to the consistency and predictability of public transport services, including adherence to schedules and minimal service disruptions [32]. Reliable services are essential for establishing user trust and promoting consistent ridership. The use of advanced technologies, such as real-time monitoring and predictive maintenance, plays a key role in enhancing service reliability [33].

iii. Accessibility

Accessibility refers to the ease with which users can reach public transport services, including physical access for individuals with disabilities and the availability of services in underserved areas [34]. High accessibility ensures equitable access to mobility options, particularly for low-income and marginalised populations [20]. Investments in infrastructure, such as ramps, elevators, and accessible vehicles, are essential for creating inclusive transport systems [35].

iv. Travel Time

Travel time is a critical determinant of public transport attractiveness, as it directly affects user satisfaction and system efficiency. Shorter travel times are associated with higher ridership and improved accessibility to employment, education, and healthcare services [36]. Studies have shown that reducing travel time through optimised routes, express services, and real-time tracking can significantly enhance the competitiveness of public transport compared to private vehicles [37].

v. Cost of Operation

The cost of operation is a key consideration for public transport systems, as it impacts the financial sustainability of services. Efficient cost management can lead to more affordable fares and better service quality. Cost-effective operations are therefore essential for maintaining sustainable public transport systems [38].

vi. Economic Efficiency

Economic efficiency refers to the optimal use of resources to achieve the best possible outcomes in public transport systems. Efficient systems provide high-quality services at lower costs, benefiting both users and operators. Studies have shown that economic efficiency is closely linked to user satisfaction and system sustainability [39].

vii. Employment

Employment status and location influence public transport demand, particularly for commuting purposes. Accessible and reliable transport services are essential for connecting workers to job opportunities, particularly in low-income areas. Studies have shown that improved public transport can reduce unemployment and promote economic growth [40].

viii. Health Impact

Public transport systems can significantly impact user health by reducing air pollution, promoting physical activity, and providing access to healthcare services. Health-conscious designs, such as ergonomic seating and clean air standards, can enhance passenger well-being. Studies have shown that public transport use is associated with lower rates of obesity and chronic diseases [41].

ix. Equity

Equity in public transport ensures that all population groups, regardless of income, age, or physical ability, have access to affordable and reliable mobility options. Equitable systems promote social inclusion and reduce disparities in access to essential services. Targeted policies, including fare subsidies and accessible infrastructure, play a crucial role in achieving transport equity [17].

x. Vehicle Occupancy Rate

Vehicle occupancy rate reflects the efficiency of public transport systems in utilising available capacity. High occupancy rates indicate effective resource use and reduced environmental impact, while low rates may suggest inefficiencies. Optimising occupancy rates through demand-responsive services and dynamic pricing can improve system sustainability [42].

xi. Waiting Time

Waiting time is a key factor influencing user satisfaction and the overall efficiency of public transport systems. Excessive waiting times can deter potential users and reduce the competitiveness of public transport [43]. Strategies such as real-time information systems, frequent service intervals, and optimised scheduling can minimise waiting times and improve user experience [44].

xii. Safety and Security

Safety and security are fundamental concerns for public transport users, particularly vulnerable groups such as women, children, and the elderly. A safe and secure environment encourages ridership and fosters user confidence [45]. Measures such as adequate lighting, surveillance systems, and visible staff presence play a key role in improving perceived safety and reducing crime in public transport systems [46].

xiii. Environmental Taxes and Pricing Mechanisms

Environmental taxes and pricing mechanisms are crucial tools for promoting sustainable public transport systems. By encouraging the use of public transport rather than private vehicles, these policies can lower emissions and ease traffic. Well-designed pricing strategies therefore support the achievement of environmental and social sustainability objectives [47].

xiv. Capital Investment

Infrastructure development and maintenance for public transport depend heavily on capital investment. Sufficient finance promotes long-term sustainability and guarantees the provision of high-quality services. According to studies, making strategic infrastructure expenditures can result in notable gains in user satisfaction and system performance[48].

xv. Ticket Pricing Structure (Monthly & Daily)

The cost of tickets, such as daily and monthly rates, has a big impact on how often people utilise public transport. Flexible and reasonably priced fare options encourage frequent travel and broaden accessibility across user groups, reinforcing the role of fare policies in fostering inclusive and equitable public transport use [49].

xvi. Family Size

Mobility patterns and transportation needs are influenced by family size, especially in households with children. Accessibility and user happiness can be improved by public transport systems that provide family-friendly features like stroller-friendly cars and family discounts. Family-oriented transport policies therefore contribute to more sustainable and inclusive mobility systems [50].

xvii. Date and Time of Journey

Demand and service planning for public transport are impacted by the trip date, including peak and off-peak times. Service schedules and resource allocation can be improved by having a better understanding of ridership fluctuations throughout time. For instance, providing more services during busy times might ease crowding and boost customer satisfaction [51].

xviii. Loyalty Programs

The desire of users to regularly select public transport over alternative modes of transportation is reflected in their loyalty. User loyalty is affected by elements like service quality, dependability, and cost. Increasing ridership and lowering dependency on private vehicles can be achieved by cultivating loyalty through satisfying user experiences [52].

xix. Type of Journey

User preferences and the demand for transportation are influenced by the type of journey, such as shopping, leisure, or commuting. Enhancing system efficiency and customer happiness can be achieved by customising services to fit the requirements of various travel types. For instance, flexible routes for leisure travellers and rapid services for commuters can improve the user experience overall [53].

xx. Education Level

Because higher education is frequently linked to a greater understanding of social and environmental issues, education level can have an impact on the use of public transport. Student-focused public transport programs, such as reduced rates and school bus services, can encourage sustainable mobility and ease traffic [54].

xxi. Gender

Planning for public transport must take gender into account because women frequently confront particular difficulties, such as caring duties and safety concerns. Women-only carriages and enhanced security measures are two examples of gender-sensitive policies that might improve public transport networks' accessibility and inclusivity [55].

In summary, existing studies consistently highlight affordability, reliability, and accessibility as the most influential indicators of sustainable public transport, underscoring the importance of user-centred and equitable service design. However, socio-demographic and behavioural factors, such as gender, safety, and education, remain less systematically examined despite their significance for inclusive mobility. These gaps reinforce the need for the present study’s structured, multi-criteria approach to assess and prioritise socio-economic sustainability indicators, thereby contributing to a more balanced understanding of public transport systems.

2.4 Multi-Criteria Decision-Making (MCDM) in Transport Planning

MCDM methods have been widely adopted in transport planning to address complex, multi-dimensional problems that involve conflicting objectives and stakeholder preferences. Among these methods, the AHP was developed by Saaty, which is one of the most widely used due to its ability to structure complex decision problems hierarchically and facilitate pairwise comparisons of criteria [56]. AHP has been applied in various transport-related studies, including route optimisation, mode choice analysis, policy evaluation and sustainability assessments. For instance, AHP has been applied to evaluate the sustainability of urban transport systems, demonstrating its effectiveness in integrating economic, environmental, and social criteria [57].

However, the application of AHP in public transport planning has been limited by several challenges. One major limitation is the cognitive burden placed on experts during pairwise comparisons, particularly when dealing with a large number of criteria [58]. This can lead to inconsistencies in judgments and reduce the reliability of results. Additionally, traditional AHP does not account for the prioritisation of criteria, which can result in inefficiencies in the decision-making process.

To address these limitations, researchers have explored hybrid MCDM approaches that combine AHP with other techniques, such as fuzzy logic, data envelopment analysis (DEA), and machine learning. For example, fuzzy AHP has been applied to manage uncertainty and imprecision in expert judgments [59], while the integration of AHP with DEA has been used to enhance the efficiency of sustainability assessments [60]. Although these hybrid approaches offer greater flexibility and robustness, they often lack the transparency and interpretability required for effective policy-making.

2.5 Parsimonious Analytic Hierarchy Process (PAHP)

PAHP is a relatively recent development in MCDM that addresses some of the limitations of traditional AHP. PAHP introduces a prioritisation mechanism that allows decision-makers to rank criteria based on their relative importance, reducing the cognitive load associated with pairwise comparisons while maintaining analytical robustness, so PAHP has emerged as an effective extension of AHP [8]. This approach is particularly useful in complex decision problems, such as sustainability assessments, where the number of criteria can be overwhelming. Studies have shown that PAHP enhances decision efficiency and accuracy, involving multiple stakeholders [61], [62].

The priority-based Analytic Hierarchy Process (PAHP) has been applied across several fields, including supply chain management, healthcare, and environmental planning. Its use in prioritising sustainability indicators within green supply chain management has demonstrated its effectiveness in streamlining decision-making processes [63]. However, applications of PAHP in public transport planning remain limited, indicating a notable gap in the existing literature.

2.6 Research Gaps and Contributions

While existing studies have made significant contributions to the field of public transport sustainability, several gaps remain. First, there is a lack of consensus on how to systematically prioritise and evaluate social sustainability indicators, particularly in the context of MCDM. Second, traditional MCDM methods such as AHP are often criticised for their computational complexity and reliance on expert judgment, limiting their practical applicability. Finally, there is a need for more scalable and adaptable frameworks that can be applied across diverse metropolitan regions.

This study addresses these gaps by introducing a hybrid PAHP-AHP framework for evaluating social sustainability in public transport. By leveraging PAHP to reduce the number of indicators and AHP to conduct pairwise comparisons, the proposed approach offers a more efficient and scalable solution for decision-making. The methodology not only addresses the limitations of existing MCDM techniques but also provides a robust foundation for future research in this area.

3. Methodology

This study applies Multi-Criteria Decision-Making (MCDM) techniques to evaluate public transport sustainability by prioritising key Socio-economic indicators. The methodological framework, illustrated in Figure 1, outlines a structured approach beginning with the identification of 21 Socio-economic sustainability indicators. These indicators were derived from a thorough literature review and expert consultations, ensuring their relevance and applicability to public transport sustainability assessment. The indicators include travel time, security, accessibility, waiting time, reliability, affordability, vehicle occupancy rate, equity, health, age, loyalty, date of journey, family size, type of journey, employment, education, gender, cost of operation, economic efficiency, and environmental taxes. A predefined framework based on existing studies and sustainability models guided the selection, categorising indicators into key aspects such as travel time, accessibility, affordability, operational efficiency, financial sustainability, and social equity. , and safety. Experts, including academics, policymakers, and consultants, validated and refined these indicators through a structured evaluation process. This approach ensured that the selected indicators accurately represent the social dimension's impact on transport sustainability while aligning with broader sustainability assessment methodologies.

A two-stage evaluation was conducted using the PAHP and the traditional AHP to streamline the decision-making process. In the first round, PAHP was employed to gather assessments from a panel of 80 experts, including university professors, PhD researchers, policymakers, and transportation consultants. A total of 45 valid responses were obtained, and experts ranked the indicators on a scale from 0 to 100. Out of 80 experts invited, 45 valid responses were obtained, representing a 56% response rate. This rate is consistent with expert-based MCDM studies, where completion often depends on the complexity of pairwise comparisons [8]. Non-responses were primarily due to incomplete submissions or time constraints. Based on the ranking results, the number of indicators was reduced from 21 to 3 as reference indicators (upper-mid-lower).

In the second round, the same group of 45 experts participated in a traditional AHP pairwise comparison survey to further evaluate and prioritise the 3 selected indicators. The experts scored the indicators, and the process concluded by prioritising these key sustainability indicators in public transport. The final prioritization results guided the identification of the most critical social indicators influencing public transport sustainability.

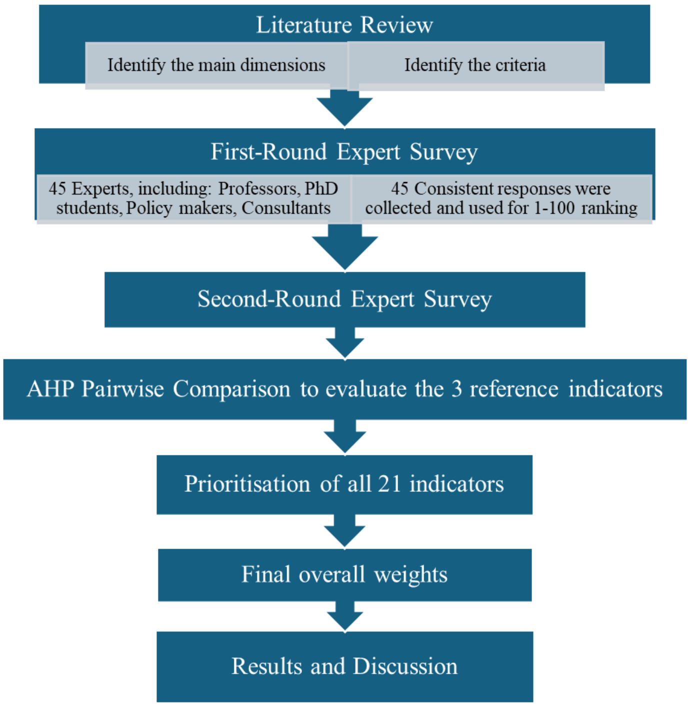

Fig 1. The methodological framework of the PAHP process.

3.1 Survey Design and Implementation

The survey was designed to ensure a robust and systematic evaluation of Socio-economic sustainability indicators. It was conducted in two phases, each tailored to the specific requirements of PAHP and AHP methodologies.

3.1.1 Survey Design:

i. Indicator Selection: The 21 Socio-economic sustainability indicators were identified through a comprehensive literature review and validated by a panel of experts. These indicators included travel time, security, accessibility, waiting time, reliability, affordability, vehicle occupancy rate, equity, health, age, loyalty, date of journey, family size, type of journey, employment, education, and gender.

ii. Questionnaire Development: Two distinct questionnaires were developed for the PAHP and AHP phases. The PAHP questionnaire asked experts to rank the 21 indicators on a scale of 0 to 100 based on their perceived importance. The AHP questionnaire involved pairwise comparisons of the top 3 indicators using Saaty's nine-point scale.

iii. Expert Selection: Experts were selected based on their academic qualifications, professional experience, and direct involvement in public transport planning, sustainability, and policy-making. The diverse backgrounds of the experts ensured a comprehensive evaluation of the indicators, incorporating both theoretical insights and practical applications.

3.1.2 Survey Implementation:

i. First Round (PAHP): The PAHP questionnaire was distributed to 80 experts via an online survey platform. Experts were asked to rank the 21 indicators based on their perceived importance. A total of 45 valid responses were collected, and the results were used to reduce the number of indicators from 21 to 3.

ii. Second Round (AHP): The AHP questionnaire was distributed to the same 45 experts who participated in the first round. Experts were asked to compare the 3 selected indicators pairwise using Saaty's nine-point scale. The responses were collected and analysed to determine the final weights of the indicators.

3.2 Data Validation:

To ensure the validity and consistency of expert responses, the consistency ratio (CR) analysis was conducted for both survey rounds. A CR below 0.10 indicated acceptable logical coherence. In cases where inconsistencies were detected, experts were asked to revise their responses. Geometric mean aggregation was applied to consolidate responses, reducing individual bias and ensuring the robustness of the results.

3.3 The AHP Approach

AHP is a widely used MCDM method that enables decision-makers to systematically structure complex problems through pairwise comparisons and mathematical calculations. Figure 2 presents the hierarchical structure of the AHP model, which consists of three levels: the main goal (public transport sustainability), evaluation criteria (economic-social indicators), and alternatives.

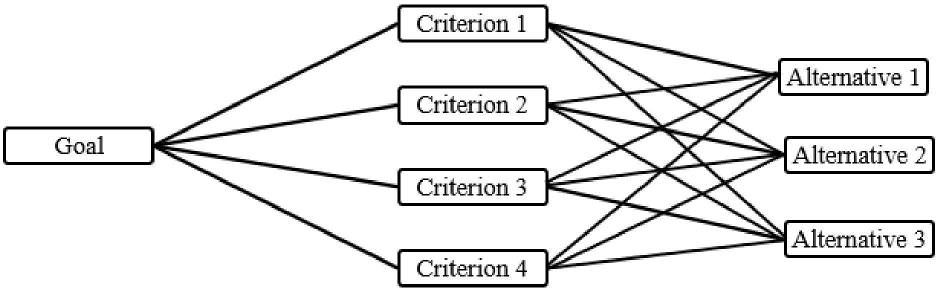

Fig 2. A standard MCDM hierarchy.

The implementation of AHP follows these key steps:

i. Problem Definition: Clearly define the research objective—prioritising social sustainability indicators for public transport.
ii. Hierarchy Development: Structure the problem into three levels: overarching goal, evaluation criteria (indicators), and alternatives, 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. Pairwise Comparisons: Experts assess the relative importance of indicators using Saaty's nine-point scale (Table 1).

The process involves assessing pairwise comparison matrices that measure indicators and alternatives concerning the objective. Consequently, matrix D (n × n) is formulated based on the number of options A (Equation 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.

Table 1
The AHP preference's pairwise comparison ranking [64].

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

i. Matrix Formation and Eigenvector Calculation: Pairwise comparison matrices are constructed, and the relative weights of indicators are determined using eigenvalue computations.
ii. Consistency Evaluation: The consistency index (CI) and consistency ratio (CR) are calculated to ensure logical coherence in expert judgments. A CR below 0.10 indicates an acceptable level of consistency.
iii. Weight Aggregation: Responses from multiple experts are aggregated using the geometric mean.

Mathematical Formulation of AHP:

Pairwise comparison matrices are represented as follows:

$$D = \begin{bmatrix} 1 & C_{12} & \cdots & C_{1n} \\ \vdots & \ddots & \cdots & \vdots \\ \frac{1}{C_{1n}} & \frac{1}{C_{2n}} & \cdots & 1 \end{bmatrix} \tag{1}$$

Equation 2 uses a reciprocal matrix to restructure the matrix where $C_{ij} = \frac{1}{C_{ij}}$

$$D = \begin{bmatrix} 1 & C_{12} & \cdots & C_{1n} \\ \vdots & \ddots & \cdots & \vdots \\ \frac{1}{C_{1n}} & \frac{1}{C_{2n}} & \cdots & 1 \end{bmatrix} \begin{bmatrix} W1 \\ W2 \end{bmatrix} = \lambda\text{max} \begin{bmatrix} W1 \\ W2 \end{bmatrix} \tag{2}$$

The weight of the criteria is obtained by computing the eigenvector using Equation 3.

$$DW = \lambda_{\max}\mathrm{W} \tag{3}$$

Consistency evaluation entails calculating the consistency index (CI) using eigenvalue computati ons following pairwise comparisons and the acquisition of criteria weights. Λmax As follows:

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

Decision consistency is measured using CI's consistency ratio (CR), where n is the matrix size. Acceptable consistency is shown by a CR less than 0.10. On the other hand, bias in the judgment matrix is indicated if the CR is greater than 0.10. It is necessary to examine and improve assessments in order to produce a consistent matrix. The following formula can be used to get the CR:

$$CR{=}CI\,/\,RI \tag{5}$$

where RI stands for mean random consistency, and Table 2 contains the precise values of RI.

Numerous decision-makers and assessors are included in AHP surveys. As shown in the following calculation, the geometric mean must therefore be used to consolidate the individual ratings.

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

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

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

3.4 The PAHP Approach

The basic goal of the PAHP approach is to avoid lengthy pairwise comparisons and reduce the number of questions asked in a survey. Because it can simplify the decision-making process by lowering the number of pairwise comparisons needed, PAHP was selected over other Multi-Criteria Decision-Making (MCDM) techniques. Because of this, PAHP is especially effective and requires less mental effort from specialists while yet offering strong and trustworthy criterion prioritisation. Particularly in complicated scenarios including many sustainability indicators, PAHP improves practicality while maintaining accuracy and consistency in outcomes, in contrast to classical AHP alone, which can become burdensome with big datasets [65]. The following describes the next steps of the PAHP approach, which was first presented by [66].

i. A direct assessment evaluates the indications Cj in relation to option A using a predetermined scale (e.g., 0–100). As a result, all criteria undergo the normalisation procedure. For every j = 1…n and for all t = 1…n, the normalised values for the requirements are denoted by λj. After that, these normalised indicators are arranged in ascending order so that new ratings can be determined using the normalised values for each indicator. The notation for these updated scores is r_j.
ii. Based on its revised ranking inside the Cj criteria, the reference point indication (Cr) is selected. As shown in Table 3, the overall number of indicators determines the specific count of based indicators, represented by t.
iii. The normalised AHP values for the Cr indicators are obtained by performing the AHP above pairwise comparison procedures with the specified number of indicators, t. The symbol for these AHP scores is u(Cj). The corresponding ratings verify that the monotonic character is maintained, guaranteeing that if u $C_{r1} \geq C_{r2}$ $then$ $D(r_{j1}) > D(r_{j2})$.
iv. Using linear interpolation, the scores for the remaining indicators, represented as u(rj) (which include all criteria outside the references criteria) are calculated as follows [67]:

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

Table 3
The minimum indicators count Cj with the given indicator number [68].

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

Because of its capacity to strike a compromise between simplicity and analytical rigour, PAHP was chosen above other MCDM techniques. While maintaining the accuracy of the results, PAHP offers a more efficient decision-making procedure than TOPSIS or Fuzzy AHP, which bring greater computing complexity.

3.5 Advantages of the Hybrid PAHP-AHP Framework

The hybrid PAHP-AHP framework offers several advantages, making it a powerful tool for evaluating public transport sustainability. First, efficiency is achieved as PAHP reduces the number of pairwise comparisons, minimising cognitive burden and saving time for experts. Second, accuracy is ensured through AHP, which provides a rigorous and consistent prioritisation of indicators, maintaining the integrity of the decision-making process. Third, the framework demonstrates scalability, as it can be applied to large datasets and adapted to diverse contexts, making it suitable for various urban and regional settings. Finally, the framework emphasises practicality by delivering actionable insights that policymakers and urban planners can use to make informed decisions.

While AHP and PAHP inherently assume indicator independence, this simplification facilitates transparency and analytical consistency. However, we acknowledge potential interdependencies such as between accessibility and equity and note that future studies could employ Analytic Network Process (ANP) or Fuzzy AHP to capture these relationships more dynamically. Together, these advantages ensure that the hybrid PAHP-AHP framework provides a comprehensive, systematic, and data-driven approach to evaluating public transport sustainability, making it an effective tool for guiding policy and planning decisions [65].

4. Results

4.1 Weights of the Indicators

The evaluation of social sustainability indicators in public transport revealed important insights into their relative significance and influence on system efficiency and user satisfaction. The analysis began with the direct assessment of 21 indicators, followed by a normalisation process to ensure comparability across the diverse criteria. The results, summarised in Table 4, present the normalised values of these indicators in ascending order, providing a clear understanding of their hierarchical importance within the overall sustainability framework.

Table 4
Direct Evaluation and Normalised Values of Socio-economic Indicators.

	Indicators	**Normalization value λ(C)**
	Socio-economic criteria	
1	Affordability	7.83
2	Reliability	6.73
3	Accessibility	6.52
4	Travel Time	6.37
5	Cost of Operation	6.13
6	Economic Efficiency	5.93
7	Employment	5.7
8	Health Impact	5.531
9	Equity	5.42
10	Vehicle Occupancy Rate	5.11
11	Waiting Time	4.93
12	Safety and Security	4.76
13	Environmental Taxes and Pricing Mechanisms	4.53
14	Capital Investment	4.3
15	Ticket Pricing Structure (Monthly & Daily)	4.15
16	Family Size	3.93
17	Date and Time of Journey	3.75
18	Loyalty Programs	3.61
19	Type of Journey	3.33
20	Education Level	2.84
21	Gender	2.63

Based on the normalised values, three reference indicators were selected for further pairwise comparisons: travel time (highest rank), health (middle rank), and gender (lowest rank). These indicators were chosen to represent the spectrum of importance, ensuring a balanced and comprehensive evaluation.

The second phase of the analysis employed the PAHP to refine the results. Pairwise comparison matrices were constructed, and the consistency ratio (CR) for all calculations was confirmed to be below 10%, indicating a high level of reliability in expert judgments. Table 5 summarises the scores and rankings of the reference indicators.

Table 5
AHP weight of the Reference Indicators.

Indicators	**value u(Cr)**	**Ranking**
Social-based indicators		
Affordability	0.471	1
Waiting Time	0.432	2
Gender	0.074	3

The final weights for all social indicators were derived through linear interpolation, as outlined in Equation 7. Table 6 presents the comprehensive ranking and weights, providing a clear prioritisation of the indicators.

Table 6
Final Overall Weight of Social Indicators.

Indicators	**Ranking**	**Final PAHP weight**	**Final overall weight**
Affordability	1	0.471	0.0645
Reliability	2	0.456	0.0625
Accessibility	3	0.453	0.0621
Travel Time	4	0.451	0.0618
Cost of Operation	5	0.448	0.0614
Economic Efficiency	6	0.445	0.0610
Employment	7	0.426	0.0603
Health Impact	8	0.441	0.0600
Equity	9	0.439	0.0595
Vehicle Occupancy Rate	10	0.434	0.0591
Waiting Time	11	0.432	0.0584
Safety and Security	12	0.406	0.0555
Environmental Taxes	13	0.370	0.0506
Capital Investment	14	0.334	0.0457
Ticket Pricing Structure	15	0.311	0.0425
Family Size	16	0.177	0.0310
Date and Time of Journey	17	0.218	0.0298
Loyalty Programs	18	0.227	0.0251
Type of Journey	19	0.183	0.0242
Education Level	20	0.107	0.0147
Gender	21	0.074	0.0102

4.2 Interpretation of Results

The results highlight the critical role of Affordability as the most influential Socio-economic indicator, reflecting its direct impact on user satisfaction and system efficiency. Reliability and Accessibility follow closely, underscoring the importance of inclusive transport services. Waiting time and Vehicle Occupancy Rate also rank highly, emphasising the need for consistent and timely services to enhance user experience.

At the lower end of the spectrum, gender and education received the lowest weights. While these indicators are not insignificant, their relatively lower prioritisation suggests that other factors, such as affordability and travel time, are perceived as more immediate concerns by experts and stakeholders. This finding aligns with previous research, which has highlighted the indirect impact of gender and education on public transport sustainability compared to operational and service-related factors.

5. Discussion

The analysis of social sustainability indicators in public transport, using both direct evaluation and the PAHP, offers important insights into stakeholder priorities and the perceived impact of various socio-economic factors on system performance. The findings reveal a distinct hierarchy of importance, with Affordability emerging as the most critical indicator. This outcome reinforces the prevailing understanding that cost is a decisive factor influencing user satisfaction and accessibility, particularly for lower-income populations who are often most dependent on public transport systems. This finding aligns with similar studies conducted in Latin America [31] and Asia [3], which identified fare affordability as a key determinant of transport accessibility and equity. However, regional variations are evident, with greater emphasis placed on reliability and comfort in high-income contexts [69]. To enhance affordability, authorities such as municipal transport agencies should implement fare integration and subsidy mechanisms targeting low-income users. Reliability improvements require investment in fleet maintenance, real-time tracking, and infrastructure upgrades led by operators and regional transport authorities. Enhancing accessibility involves coordinated planning between urban designers and local governments to ensure barrier-free routes and inclusive station designs. Closely following affordability were Reliability and Accessibility, which confirm the significance of consistent service quality and the ease of reaching transport nodes. These elements are frequently cited in the literature as fundamental components of equitable and sustainable transport systems. Their high ranking suggests that improving punctuality, reducing cancellations, and ensuring the physical and geographical accessibility of transport services can substantially enhance public transport use and trust. Interestingly, Travel Time, Cost of Operation, and Economic Efficiency also featured prominently. These indicators reflect user- and operator-side concerns, emphasising a dual focus in sustainability discourse: maximizing user convenience while maintaining financial viability for service providers. Such a balance is essential for long-term sustainability and efficiency.

Health Impact, Employment, and Equity ranked in the middle tier of importance. While these indicators may not exert as immediate or tangible an influence as affordability or reliability, their inclusion in the upper half of the ranking highlights an increasing awareness of public transport's broader societal implications, including its role in promoting inclusive economic opportunities and minimizing adverse health outcomes.

At the lower end of the ranking, Gender, Education Level, and Type of Journey were identified as less influential indicators. Although these socio-demographic variables are widely recognized as critical for ensuring equitable access and user satisfaction, their lower weight in this study may reflect the expert participants' focus on operational and economic aspects, such as affordability and reliability. Nevertheless, the low importance assigned to Gender and Safety warrants further reflection. Prior research demonstrates that gendered travel behaviour, personal security perceptions, and safety-related concerns strongly influence women's and vulnerable users' willingness to use public transport [46]; [55]. The relatively low prioritisassions of these indicators in the present study suggests potential gaps in stakeholder awareness or methodological limitations associated with expert-centric evaluation approaches. Future studies should incorporate passenger-level behavioural and safety data to capture these nuanced social dimensions more comprehensively and ensure a more inclusive understanding of public transport sustainability.

The use of PAHP and the successful consistency check across pairwise comparisons also strengthens the robustness of these results. The method allowed a structured and reliable prioritization process, leading to a comprehensive and defensible ranking of indicators. The results thus provide a solid foundation for policymakers aiming to design more inclusive and socially sustainable public transport systems.

In summary, prioritizing indicators such as affordability, reliability, and accessibility confirms current policy trends emphasizing user-cantered service design. Meanwhile, the lower weighting of demographic factors indicates a potential need for more nuanced frameworks or targeted interventions to better account for all user groups' diverse needs. These insights are valuable for developing targeted strategies and resource allocations to enhance the overall social sustainability of public transport systems.

6. Conclusions

This study evaluated and prioritized social sustainability indicators in public transport through a structured multi-criteria decision-making approach, combining direct normalization and the Parsimonious Analytic Hierarchy Process (PAHP). The results revealed that Affordability, Reliability, and Accessibility are the most influential socio-economic factors in shaping user satisfaction and the overall efficiency of transport systems. These findings emphasize the importance of user-centric service design and affordability-focused policies to enhance the social sustainability of public transport systems.

Health Impact, Equity, and Employment indicators also held notable importance, reflecting an increased awareness of the broader societal benefits of sustainable public transport systems. Conversely, demographic factors such as Gender, Education Level, and Type of Journey received lower weights, suggesting that they are currently perceived as less influential in direct decision-making, though their indirect effects remain significant.

The methodological rigour of the PAHP approach, supported by consistency verification, reinforces the reliability of the results and provides a sound foundation for policymaking and investment prioritisation. However, several limitations should be acknowledged. The potential oversimplification may arise from PAHP's reduction in pairwise comparisons, expert bias in survey responses, and limited consideration of uncertainty in decision-making. Future research could address these by integrating fuzzy logic to account for uncertainty, using larger and more diverse expert panels, and applying sensitivity analysis to test the robustness of results. Additionally, other MCDM tools, such as the Analytic Network Process (ANP), could be explored to capture interdependencies among criteria, while Fuzzy AHP or TOPSIS could provide a more nuanced assessment by incorporating uncertainty and ranking alternatives more dynamically.

The study's expert-centric evaluation may not fully capture the perspectives of diverse user groups, underscoring the need for broader stakeholder engagement particularly among passengers of different socio-economic and demographic backgrounds. Moreover, the findings are context-specific to the Hungarian public transport environment and may not be directly generalizable to other urban settings.

In addition, the analysis relied on perceived importance rather than observed behavioural data, which limits insight into actual user responses. Future research should integrate behavioural datasets and longitudinal analysis to examine how the importance of social indicators evolves over time in response to policy or technological changes. Lastly, combining the present social sustainability framework with environmental and technical dimensions would provide a more comprehensive understanding of sustainable public transport systems.

Addressing these limitations will enhance the validity and applicability of future evaluations and contribute to the development of more inclusive, resilient, and user-responsive transport policies and planning strategies.

Author Contributions

Conceptualisation, Hiba Solieman and Ammar Al-lami; methodology, Ammar Al-lami.; software, Ammar Al-lami; validation, Hiba Solieman and Ammar Al-lami; formal analysis, Ammar Al-lami; investigation, Ammar Al-lami; resources, Ammar Al-lami; data curation, Ammar Al-lami; writing—original draft preparation, Hiba Solieman; writing—review and editing, Hiba Solieman; visualisation, Hiba Solieman; supervision, Hiba Solieman and Ammar Al-lami; project administration, Hiba Solieman; funding acquisition, Hiba Solieman and Ammar Al-lami. All authors have read and agreed to the published version of the manuscript."

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to privacy and expert confidentiality agreements, the dataset is not publicly available.

Conflicts of 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. No funders had a role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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References

[1] Y. Chen, A. Bouferguene, Y. Shen, and M. Al-Hussein, "Assessing accessibility-based service effectiveness (ABSEV) and social equity for urban bus transit: A sustainability perspective," Sustainable Cities and Society, vol. 44, pp. 499-510, Jan. 2019. https://doi.org/10.1016/j.scs.2018.10.003

[2] N. Cuthill, M. Cao, Y. Liu, X. Gao, and Y. Zhang, "The Association between Urban Public Transport Infrastructure and Social Equity and Spatial Accessibility within the Urban Environment: An Investigation of Tramlink in London," Sustainability, vol. 11, no. 5, Art. no. 5, Jan. 2019. https://doi.org/10.3390/su11051229

[3] M. Ahmad et al., "Investigating the Key Factors Affecting Public Transport Ridership in Developing Countries through Structural Equation Modeling," Sustainability, vol. 16, no. 11, pp. 1-25, 2024, Accessed: Feb. 15, 2025. [Online]. Available: https://ideas.repec.org//a/gam/jsusta/v16y2024i11p4426-d1400372.html. https://doi.org/10.3390/su16114426

[4] S. Jia, "Economic, environmental, social, and health benefits of urban traffic emission reduction management strategies: Case study of Beijing, China," Sustainable Cities and Society, vol. 67, p. 102737, Apr. 2021. https://doi.org/10.1016/j.scs.2021.102737
[5] N. Hanzah and H. Sulaiman, "An Empirical Analysis of Social Dimension Factors Towards Better IT Service Quality for Malaysian Public Agencies," International Journal of Engineering & Technology, vol. 7, no. 4.35, Art. no. 4.35, Nov. 2018. https://doi.org/10.14419/ijet.v7i4.35.22920
[6] T. Borchers, D. Wittowsky, and R. Augusto Souza Fernandes, "A Comprehensive Survey and Future Directions on Optimising Sustainable Urban Mobility," IEEE Access, vol. 12, pp. 63023-63048, Jan. 2024. https://doi.org/10.1109/ACCESS.2024.3393470
[7] Kumar and R. A, "An MCDM framework for assessment of social sustainability indicators of the freight transport industry under uncertainty. A multi-company perspective," Journal of Enterprise Information Management, vol. 33, no. 5, pp. 1023-1058, Apr. 2020. https://doi.org/10.1108/JEIM-09-2019-0272
[8] S. Duleba, "Introduction and comparative analysis of the multi-level parsimonious AHP methodology in a public transport development decision problem," Journal of the Operational Research Society, vol. 73, no. 2, pp. 230-243, Mar. 2022. https://doi.org/10.1080/01605682.2020.1824553
[9] S. Kim, M. E. Lewis, and C. C. White, "Optimal vehicle routing with real-time traffic information," IEEE Transactions on Intelligent Transportation Systems, vol. 6, no. 2, pp. 178-188, Jun. 2005. https://doi.org/10.1109/TITS.2005.848362
[10] M. Vogiatzaki, S. Zerefos, and M. Hoque Tania, "Enhancing City Sustainability through Smart Technologies: A Framework for Automatic Pre-Emptive Action to Promote Safety and Security Using Lighting and ICT-Based Surveillance," Sustainability, vol. 12, no. 15, Art. no. 15, Jan. 2020. https://doi.org/10.3390/su12156142
[11] L. A. Guzman and D. Oviedo, "Accessibility, affordability and equity: Assessing 'pro-poor' public transport subsidies in Bogotá," Transport Policy, vol. 68, pp. 37-51, Sep. 2018. https://doi.org/10.1016/j.tranpol.2018.04.012
[12] J. C. Muñoz, J. Soza-Parra, and S. Raveau, "A comprehensive perspective of unreliable public transport services' costs," Transportmetrica A: Transport Science, vol. 16, no. 3, pp. 734-748, Jan. 2020. https://doi.org/10.1080/23249935.2020.1720861
[13] R. Cervero, "Bus Rapid Transit (BRT): An Efficient and Competitive Mode of Public Transport," Oct. 2013, Accessed: Feb. 25, 2025. [Online]. Available: https://escholarship.org/uc/item/4sn2f5wc
[14] Glazener and H. Khreis, "Transforming Our Cities: Best Practices Towards Clean Air and Active Transportation," Curr Envir Health Rpt, vol. 6, no. 1, pp. 22-37, Mar. 2019. https://doi.org/10.1007/s40572-019-0228-1
[15] V. S. Krishnan, H. Solieman, S. Moslem, and F. Pilla, "Inclusive sustainable transportation planning: A qualitative analysis involving diverse stakeholders perspectives," Case Studies on Transport Policy, vol. 19, p. 101393, Mar. 2025. https://doi.org/10.1016/j.cstp.2025.101393
[16] Al-lami and A. Torok, "Sustainability Indicators of Surface Public Transportation," Sustainability, vol. 15, no. 21, Art. no. 21, Jan. 2023. https://doi.org/10.3390/su152115289
[17] T. Litman, "Evaluating transportation equity," May 2011, Accessed: Feb. 16, 2025. [Online]. Available: https://policycommons.net/artifacts/1226889/evaluating-transportation-equity/1779960/
[18] M. Friman, K. Lättman, and L. E. Olsson, "Public Transport Quality, Safety, and Perceived Accessibility," Sustainability, vol. 12, no. 9, Art. no. 9, Jan. 2020. https://doi.org/10.3390/su12093563
[19] Tiznado-Aitken, K. Lucas, J. C. Muñoz, and R. Hurtubia, "Understanding accessibility through public transport users' experiences: A mixed methods approach," Journal of Transport Geography, vol. 88, p. 102857, Oct. 2020. https://doi.org/10.1016/j.jtrangeo.2020.102857
[20] K. Lucas, "Transport and social exclusion: Where are we now?," Transport Policy, vol. 20, pp. 105-113, Mar. 2012. https://doi.org/10.1016/j.tranpol.2012.01.013
[21] G. Currie and A. Delbosc, "Exploring the trip chaining behaviour of public transport users in Melbourne," Transport Policy, vol. 18, no. 1, pp. 204-210, Jan. 2011. https://doi.org/10.1016/j.tranpol.2010.08.003
[22] Jaber, H. Ashqar, and B. Csonka, "Determining the Location of Shared Electric Micro-Mobility Stations in Urban Environment," Urban Science, vol. 8, no. 2, p. 64, Jun. 2024. https://doi.org/10.3390/urbansci8020064
[23] M. Marzouk and M. Sabbah, "AHP-TOPSIS social sustainability approach for selecting supplier in construction supply chain," Cleaner Environmental Systems, vol. 2, p. 100034, Jun. 2021. https://doi.org/10.1016/j.cesys.2021.100034
[24] J. Rohács and D. Rohács, "Total impact evaluation of transportation systems," Transport, vol. 35, no. 2, Art. no. 2, May 2020. https://doi.org/10.3846/transport.2020.12640

[25] S. Sultana, D. Salon, and M. Kuby, "Transportation sustainability in the urban context: a comprehensive review," Urban Geography, vol. 40, no. 3, pp. 279-308, Mar. 2019. https://doi.org/10.1080/02723638.2017.1395635
[26] V. R. Vuchic, "Urban Transit Systems and Technology," Feb. 2007. https://doi.org/10.1002/9780470168066
[27] D. G. Chatman and R. B. Noland, "Transit Service, Physical Agglomeration and Productivity in US Metropolitan Areas," Urban Studies, vol. 51, no. 5, pp. 917-937, Apr. 2014. https://doi.org/10.1177/0042098013494426
[28] D. A. Hensher, C. Ho, and C. Mulley, "Identifying preferences for public transport investments under a constrained budget," Transportation Research Part A: Policy and Practice, vol. 72, pp. 27-46, Feb. 2015. https://doi.org/10.1016/j.tra.2014.12.002
[29] G. Currie, L. Truong, and C. De Gruyter, "Regulatory structures and their impact on the sustainability performance of public transport in world cities," Research in Transportation Economics, vol. 69, pp. 494-500, Sep. 2018. https://doi.org/10.1016/j.retrec.2018.02.001
[30] S. Moslem, H. Solieman, L. Oubahman, S. Duleba, T. Senapati, and F. Pilla, "Assessing Public Transport Supply Quality: A Comparative Analysis of Analytical Network Process and Analytical Hierarchy Process," Journal of Soft Computing and Decision Analytics, vol. 1, no. 1, Art. no. 1, Aug. 2023. https://doi.org/10.31181/jscda11202311
[31] C. Falavigna and D. Hernandez, "Assessing inequalities on public transport affordability in two latin American cities: Montevideo (Uruguay) and Córdoba (Argentina)," Transport Policy, vol. 45, pp. 145-155, Jan. 2016. https://doi.org/10.1016/j.tranpol.2015.09.011
[32] D. Levinson, "The Evolution of Transport Networks," University of Minnesota: Nexus Research Group, Working paper 200510, 2004. Accessed: Apr. 14, 2025. [Online]. Available: https://EconPapers.repec.org/RePEc:nex:wpaper:networkevolution2
[33] S. Raicu, M. Popa, and D. Costescu, "Uncertainties Influencing Transportation System Performances," Sustainability, vol. 14, no. 13, Art. no. 13, Jan. 2022. https://doi.org/10.3390/su14137660
[34] N. N. Sze and K. M. Christensen, "Access to urban transportation system for individuals with disabilities," IATSS Research, vol. 41, no. 2, pp. 66-73, Jul. 2017. https://doi.org/10.1016/j.iatssr.2017.05.002
[35] J. L. Bezyak, Sabella ,Scott, Hammel ,Joy, McDonald ,Katherine, Jones ,Robin Ann, and D. and Barton, "Community participation and public transportation barriers experienced by people with disabilities," Disability and Rehabilitation, vol. 42, no. 23, pp. 3275-3283, Nov. 2020. https://doi.org/10.1080/09638288.2019.1590469
[36] E. B. Lunke, "Commuters' satisfaction with public transport," Journal of Transport & Health, vol. 16, p. 100842, Mar. 2020. https://doi.org/10.1016/j.jth.2020.100842
[37] J. B. Ingvardson, J. K. Jensen, and O. A. Nielsen, "Analysing improvements to on-street public transport systems: a mesoscopic model approach," Public Transp, vol. 9, no. 1, pp. 385-409, Jul. 2017. https://doi.org/10.1007/s12469-016-0151-x
[38] J. Holmgren, "The efficiency of public transport operations - An evaluation using stochastic frontier analysis," Research in Transportation Economics, vol. 39, no. 1, pp. 50-57, Mar. 2013. https://doi.org/10.1016/j.retrec.2012.05.023
[39] G. Catalano, C. Daraio, M. Diana, M. Gregori, and G. Matteucci, "Efficiency, effectiveness, and impacts assessment in the rail transport sector: a state-of-the-art critical analysis of current research," International Transactions in Operational Research, vol. 26, no. 1, pp. 5-40, 2019. https://doi.org/10.1111/itor.12551
[40] J. Peña, G. Luis A, and J. Arellana, "Which dots to connect? Employment centers and commuting inequalities in Bogotá," Journal of Transport and Land Use, vol. 15, no. 1, Art. no. 1, Jan. 2022. https://doi.org/10.5198/jtlu.2022.2100
[41] S. C. Kwan and J. H. Hashim, "Chapter six - Public transport and health," in Advances in Transportation and Health, M. J. Nieuwenhuijsen and H. Khreis, Eds., Elsevier, 2020, pp. 149-173. https://doi.org/10.1016/B978-0-12-819136-1.00006-1
[42] P. Medviď, M. Gogola, and S. Kubaľák, "Occupancy of Public Transport Vehicles in Slovakia," Transportation Research Procedia, vol. 44, pp. 153-159, Jan. 2020. https://doi.org/10.1016/j.trpro.2020.02.022
[43] S. Lodhi, A. Jaiswal, and S. N. Sharma, "Assessing bus users satisfaction using discrete choice models: a case of Bhopal," Innov. Infrastruct. Solut., vol. 9, no. 11, p. 437, Oct. 2024. https://doi.org/10.1007/s41062-024-01652-w
[44] D. Lois, A. Monzón, and S. Hernández, "Analysis of satisfaction factors at urban transport interchanges: Measuring travellers' attitudes to information, security and waiting," Transport Policy, vol. 67, no. 0, Sep. 2018, Accessed: Feb. 17, 2025. [Online]. Available: https://trid.trb.org/View/1516122. https://doi.org/10.1016/j.tranpol.2017.04.004

[45] E. Sogbe, S. Susilawati, and T. C. Pin, "Scaling up public transport usage: a systematic literature review of service quality, satisfaction and attitude towards bus transport systems in developing countries," Public Transp, vol. 17, no. 1, pp. 1-44, Mar. 2025. https://doi.org/10.1007/s12469-024-00367-6

[46] G. Currie, A. Delbosc, and S. Mahmoud, "Factors Influencing Young Peoples ' Perceptions of Personal Safety on Public Transport," Journal of Public Transportation, vol. 16, no. 1, pp. 1-19, Jan. 2013, doi: 10.5038/2375-0901.16.1.1. https://doi.org/10.5038/2375-0901.16.1.1

[47] T. Munir, H. Dia, and H. Ghaderi, "A Systematic Review of the Role of Road Network Pricing in Shaping Sustainable Cities: Lessons Learned and Opportunities for a Post-Pandemic World," Sustainability, vol. 13, no. 21, Art. no. 21, Jan. 2021. https://doi.org/10.3390/su132112048

[48] Y. Xue, H. Guan, J. Corey, H. Wei, and H. Yan, "Quantifying a Financially Sustainable Strategy of Public Transport: Private Capital Investment Considering Passenger Value," Sustainability, vol. 9, no. 2, Art. no. 2, Feb. 2017. https://doi.org/10.3390/su9020269

[49] Matas, J.-L. Raymond, and A. Ruiz, "Economic and distributional effects of different fare schemes: Evidence from the Metropolitan Region of Barcelona," Transportation Research Part A: Policy and Practice, vol. 138, pp. 1-14, Aug. 2020. https://doi.org/10.1016/j.tra.2020.05.014

[50] L. McCarthy, A. Delbosc, G. Currie, and A. Molloy, "'Transit Faithfuls' or 'Transit Leavers'? Understanding mobility trajectories of new parents," Transport Policy, vol. 78, pp. 105-112, Jun. 2019. https://doi.org/10.1016/j.tranpol.2019.04.007

[51] T. Li, P. Meredith-Karam, H. Kong, A. Stewart, J. P. Attanucci, and J. Zhao, "Comparison of Door-to-Door Transit Travel Time Estimation Using Schedules, Real-Time Vehicle Arrivals, and Smartcard Inference Methods," Transportation Research Record, vol. 2675, no. 11, pp. 1003-1014, Nov. 2021. https://doi.org/10.1177/03611981211023768

[52] D. van Lierop and A. El-Geneidy, "Enjoying loyalty: The relationship between service quality, customer satisfaction, and behavioral intentions in public transit," Research in Transportation Economics, vol. 59, pp. 50-59, Nov. 2016. https://doi.org/10.1016/j.retrec.2016.04.001

[53] J. Ye, J. Bai, and W. Hao, "A Systematic Review of the Coopetition Relationship between Bike-Sharing and Public Transit," Journal of Advanced Transportation, vol. 2024, no. 1, p. 6681895, 2024. https://doi.org/10.1155/2024/6681895

[54] J. O. Moreno, C. G. Caamal-Olvera, and E. M. Luna, "Mobility and sustainable transportation in higher education: evidence from Monterrey Metropolitan Area in Mexico," International Journal of Sustainability in Higher Education, vol. 24, no. 2, pp. 339-360, Mar. 2022. https://doi.org/10.1108/IJSHE-07-2021-0276

[55] Ari, M. C. Leva, L. D'Arcy, and M. Kinahan, "Fairness and Inclusion for Users of Surface Transport-An Exploratory Thematic Study for Irish Users," Sustainability, vol. 14, no. 11, Art. no. 11, Jan. 2022. https://doi.org/10.3390/su14116480

[56] Y. Wind and T. L. Saaty, "MARKETING APPLICATIONS OF THE ANALYTIC HIERARCHY PROCESS. | EBSCOhost." Accessed: Feb. 17, 2025. [Online]. Available: https://openurl.ebsco.com/contentitem/doi:10.1287%2Fmnsc.26.7.641?sid=ebsco:plink:crawler&id=ebsco:doi:10.1287%2Fmnsc.26.7.641

[57] S. Moslem, M. K. Saraji, A. Mardani, A. Alkharabsheh, S. Duleba, and D. Esztergár-Kiss, "A Systematic Review of Analytic Hierarchy Process Applications to Solve Transportation Problems: From 2003 to 2022," IEEE Access, vol. 11, pp. 11973-11990, 2023. https://doi.org/10.1109/ACCESS.2023.3234298

[58] S. Moslem and Y. Çelikbilek, "An integrated grey AHP-MOORA model for ameliorating public transport service quality," European Transport Research Review, vol. 12, no. 1, p. 68, Dec. 2020. https://doi.org/10.1186/s12544-020-00455-1

[59] C.-W. Chang, C.-R. Wu, and H.-L. Lin, "Applying fuzzy hierarchy multiple attributes to construct an expert decision making process," Expert Systems with Applications, vol. 36, no. 4, pp. 7363-7368, May 2009. https://doi.org/10.1016/j.eswa.2008.09.026

[60] H. Hmamed, A. Benghabrit, A. Cherrafi, and N. Hamani, "Achieving a Sustainable Transportation System via Economic, Environmental, and Social Optimization: A Comprehensive AHP-DEA Approach from the Waste Transportation Sector," Sustainability, vol. 15, no. 21, Art. no. 21, Jan. 2023. https://doi.org/10.3390/su152115372

[61] S. Moslem, O. Ghorbanzadeh, T. Blaschke, and S. Duleba, "Analysing stakeholder consensus for a sustainable transport development decision by the fuzzy AHP and interval AHP," Sustainability (Switzerland), vol. 11, no. 12, p. 3271, Jan. 2019. https://doi.org/10.3390/su11123271

[62] Al-lami and Á. Török, "Assessing sustainability indicators of public transportation using PAHP," Sustainable Futures, vol. 9, p. 100500, Jun. 2025. https://doi.org/10.1016/j.sftr.2025.100500
[63] A. Moreno-Camacho, J. R. Montoya-Torres, A. Jaegler, and N. Gondran, "Sustainability metrics for real case applications of the supply chain network design problem: A systematic literature review," Journal of Cleaner Production, vol. 231, pp. 600-618, Sep. 2019. https://doi.org/10.1016/j.jclepro.2019.05.278
[64] T. L. Saaty, "Fundamentals of the analytic network process - multiple networks with benefits, costs, opportunities and risks," J. Syst. Sci. Syst. Eng., vol. 13, no. 3, pp. 348-379, Sep. 2004. https://doi.org/10.1007/s11518-006-0171-1
[65] S. Duleba and S. Moslem, "User Satisfaction Survey on Public Transport by a New PAHP Based Model," Applied Sciences, vol. 11, no. 21, Art. no. 21, Jan. 2021. https://doi.org/10.3390/app112110256
[66] F. Abastante, S. Corrente, S. Greco, A. Ishizaka, and I. M. Lami, "Choice architecture for architecture choices: Evaluating social housing initiatives putting together a parsimonious AHP methodology and the Choquet integral," Land Use Policy, vol. 78, pp. 748-762, Nov. 2018. https://doi.org/10.1016/j.landusepol.2018.07.037
[67] M. K. Smith, Sziva ,Ivett Pinke, and G. and Olt, "Overtourism and Resident Resistance in Budapest," Tourism Planning & Development, vol. 16, no. 4, pp. 376-392, Jul. 2019. https://doi.org/10.1080/21568316.2019.1595705
[68] F. Abastante, S. Corrente, S. Greco, A. Ishizaka, and I. M. Lami, "A new parsimonious AHP methodology: Assigning priorities to many objects by comparing pairwise few reference objects," Expert Systems with Applications, vol. 127, pp. 109-120, Aug. 2019. https://doi.org/10.1016/j.eswa.2019.02.036
[69] "Transit System Performance: Capacity, Productivity, Efficiency, and Utilization," in Urban Transit Systems and Technology, John Wiley & Sons, Ltd, 2007, pp. 149-201. https://doi.org/10.1002/9780470168066.ch4