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Key quality parameters (KQPs) Driving the development of sustainable multimodal Transport

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ABSTRACT

The quality of urban transport systems plays a crucial role in encouraging users to choose more sustainable modes of transport over private cars, and this topic has gained increasing attention over time. Originally, quality assessment methods were designed to evaluate and monitor local public transport (LPT) systems, supporting the transport companies that provide the service. However, as time has passed, the focus has expanded to encompass a broader range of mobility systems, emphasizing the perspective of transport users. Despite this, quality assessments have often been conducted in a fragmented manner, without a comprehensive and integrated approach. This paper addresses this gap by exploring transport quality assessment from a multimodal viewpoint, incorporating LPT, non-motorized mobility (n-MM), and electric micromobility (e-M). The aim is to identify a set of key quality parameters (KQPs) for monitoring the quality of a sustainable and multimodal urban transport system. To achieve this, the paper proposes an integrated methodology based on an international web survey, enhanced through the Analytical Hierarchy Process (AHP), and complemented by Monte Carlo simulations. This methodology enables the identification of a comprehensive list of KQPs and their characteristics, involves academic experts in gathering judgments on KQPs, facilitates the evaluation of these parameters, and ultimately defines the most promising set of seven KQPs. It could serve as a valuable decision-support tool for policymakers involved in sustainable urban and transport planning.

1. Introduction

The urban environment represents the context in which the environmental, social, and economic impacts of urbanization are most pronounced and challenging to manage. The density of population, services, and functions results in high demand for transportation, making the mobility sector the focus of public policies. Indeed, effective mobility management can significantly contribute to reducing the externalities generated by this sector, including congestion, crashes, noise, air pollution, and visual impacts. These externalities are the result of unsustainable travel, where the use of private cars prevails over alternative and less impactful modes, such as local public transport (LPT), non-motorized mobility, and electric micromobility. To incentivize communities to use less impactful travel modes, it is necessary to improve the management of urban transportation, integrate different mobility systems, and enhance the overall quality, adopting a multimodal perspective (Ferretto et al., 2026).

However, while many methodologies exist to measure transport quality, far less attention has been paid to what should be measured, and there is still limited consensus on the key dimensions and parameters that best capture the effectiveness of multimodal transport systems. Quality measures to manage urban transport systems are mostly related to individual systems, such as LPT, pedestrian, or cycling, and in most cases are not integrated into a multimodal vision. This results in limited knowledge of urban mobility supply and its potential to reduce transportation externalities, while also overlooking crucial aspects of efficiency and equity in accessibility and resource allocation (Garau et al., 2022). The result is that many transport users and citizen communities do not utilize multimodal transport options for their daily movements, instead often preferring private cars.

A key limitation of existing quality assessment approaches is that they typically rely on extensive and (sometimes) unstructured parameters lists, which provide limited guidance to decision-makers on prioritisation and trade-offs in complex multimodal contexts. As a result, planners and Public Authorities (PAs) often lack robust tools to identify which quality dimensions and parameters are truly critical for improving multimodal integration and influencing travel behaviour. This gap diminishes the practical utility of quality assessments as

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decision-support tools in urban transport planning.

This study proposes an integrated approach for identifying a set of key quality parameters (KQPs), that are useful for assessing the quality of an urban and sustainable transport system and planning its multimodal dimension based on multiple target attributes of quality. First, this approach identifies a long list of parameters, frames components, and attributes from the literature review, according to a multimodal perspective. Moreover, it involves academic experts to obtain multi-perspective judgments on each quality parameter. Next, the KQPs are assessed and refined by combining the Analytical Hierarchy Process (AHP) with algorithm-based techniques. Specifically, each KQP is evaluated using data from an international survey of academic experts in urban and sustainable transport, while the refinement phase relies on Monte Carlo simulations to account for bias and uncertainty. The procedure ultimately identifies the most robust sets of KQPs, which are subsequently compared through multiple ranking approaches. Accordingly, the study concentrates on the selection of KQPs for the planning and monitoring of multimodal, urban, and sustainable transport systems, rather than on the operational evaluation of a specific case study.

The proposed approach explicitly addresses the need to move from comprehensive but fragmented sets of parameters sets towards a reduced, prioritised, and internally consistent ones that can support strategic decision-making in multimodal planning. By combining expert judgment with a structured multicriteria weighting process and robustness analysis, the approach enables the identification of KQPs that are not only theoretically relevant but also comparatively more influential across transport modes.

This approach has been inspired by similar ones adopted by several authors over time, to analyse single components affecting the transport sector, such as sustainable transport assessment tools (Castillo and Pitfield, 2009), quality in transit service (Barabino et al., 2020), e-powered micro personal mobility vehicles (Carrara et al., 2021) and, and positioning electric charging stations (Carra et al., 2022). However, it has never been applied in relation to a multimodal mobility system. Given its effectiveness and applicability, it was proposed to fill this gap by investigating the multimodal dimension of transportation. Identifying a prioritised and weighted pool of quality parameters applicable to multimodal transport systems provides a valuable decision-support tool for practitioners and policymakers, moving beyond traditional parameter-based assessments that often lack guidance on relative importance and integration across modes. These parameters can be used to assess the current state of urban mobility supply, identify deficiencies in multimodal integration, and prioritize interventions aimed at enhancing the quality and attractiveness of sustainable alternatives to private car use. Furthermore, they can contribute to monitoring progress towards sustainability goals and guide the design of targeted policy measures or infrastructure investments (Bernal, 2016).

The paper is structured as follows. Section 2 presents the literature review on quality assessment in the field of multimodal transport systems. Section 3 presents the methodology, organised into three main phases for selecting the KQPs. Section 4 presents the results of the KQPs selection. Section 5 presents the discussion in the context of the literature. Finally, Section 6 includes conclusions and reflections on the future possible development in this research area.

2. Literature review

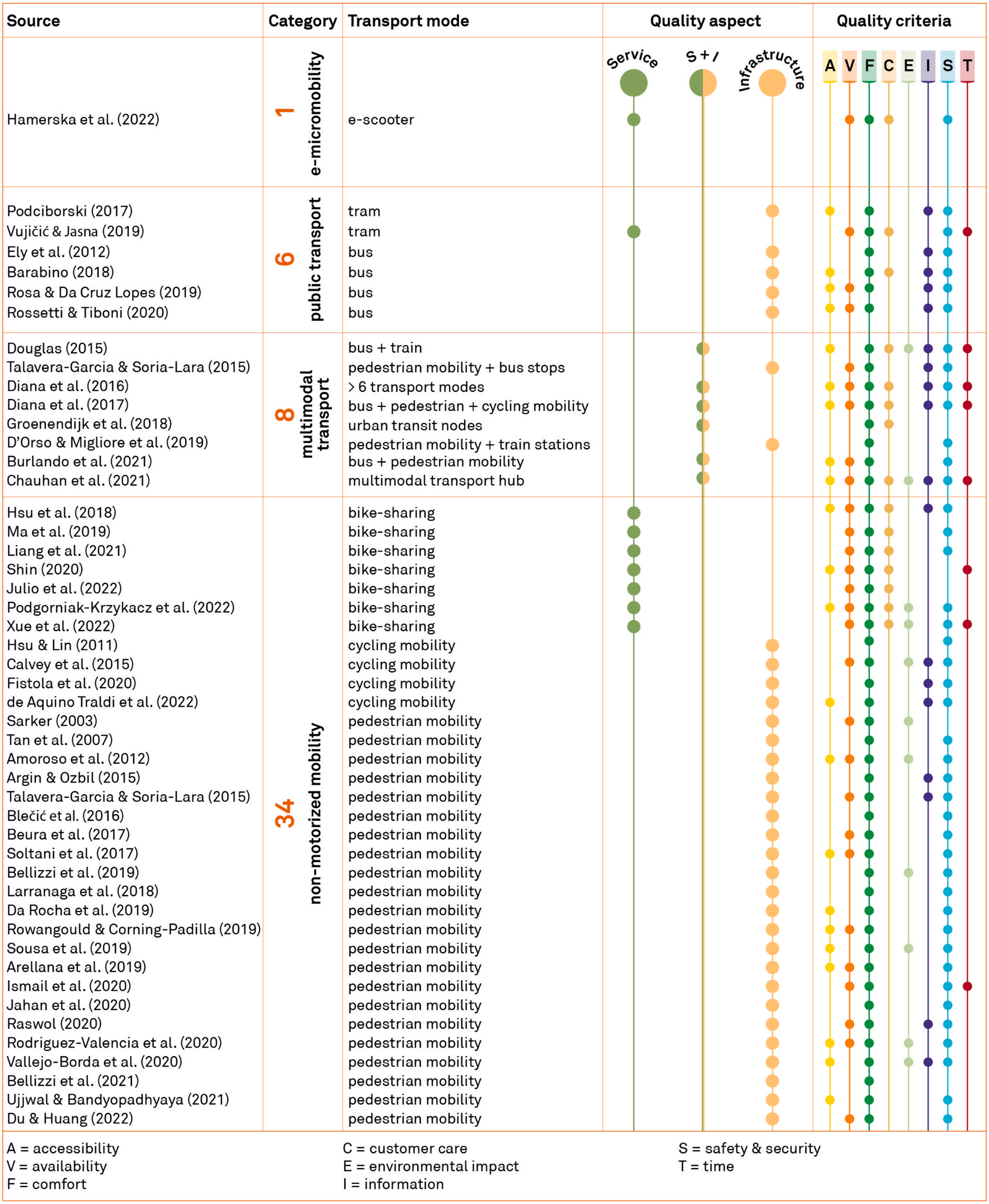
The literature review on multimodal and sustainable urban transport quality reveals a fragmented yet evolving research landscape, where a wide range of quality criteria and parameters are considered and progressively integrated into the evaluation (Ferretto et al., 2024). To provide a structured synthesis, the studies were mapped and analysed across three analytical dimensions, i.e., category, quality aspect, and transport mode (as it is shown in Fig. 1). Each dimension reflects a distinct analytical lens. The *category* groups transport systems into four overarching types: electric micromobility, public transport, multimodal transport, and non-motorized mobility, providing a functional classification of mobility systems. The *transport mode* identifies the specific means of transport considered within each category. The *quality aspect* captures whether studies focus on infrastructure, service, or both, thus distinguishing the specific components through which transport quality is assessed.

While each cluster tends to reflect a specific perspective of analysis, such as infrastructure in the case of pedestrian and cycling mobility, or service features in micromobility or bike-sharing systems, these modes, when considered in isolation, inevitably offer a partial view of what defines transport system quality. For instance, pedestrian mobility is inherently disconnected from service-related metrics, while studies on micromobility overlooking infrastructural factors and focusing on service aspects such as mobile application functions, device features, and customer service (Hamerska et al., 2022).

In this context, multimodal transport, despite being less frequently addressed in the literature, emerges as the most suitable framework for capturing the multidimensional nature of quality. By combining different modes of transport, multimodal systems allow the evaluation of both infrastructural and service-related aspects in a coherent way (Douglas, 2015; Diana et al. 2016 and 2017; Groenendijk et al., 2018; Burlando et al., 2021; Chauhan et al., 2021). They also bring attention to the interdependencies among modes, which are critical for enhancing user experience and system efficiency (Talavera-Garcia and Soria-Lara, 2015). This perspective suggests that advancing the quality of sustainable urban transport cannot rely on mode-specific approaches alone, as this would risk overlooking important quality aspects. Instead, it requires integrating multiple categories, and the diverse quality criteria they each represent, into a unified evaluative framework. Thus, multimodality becomes a methodological key to more holistic and meaningful quality assessments.

In this perspective, the raising interest in Mobility as a Service (MaaS) further reinforces the need for integrated and multimodal quality assessment frameworks (Ho & Tirachini, 2023). MaaS has emerged as a digital-enabled paradigm that aims to integrate multiple transport modes, such as public transport, shared mobility services, micromobility, and active modes, into a single, user-oriented mobility offering. Rather than promoting individual modes in isolation, MaaS seeks to leverage the complementarities among transport systems to improve efficiency, user experience, and sustainability outcomes. As highlighted in the literature, the effectiveness of MaaS strongly depends on the quality and performance of its underlying transport components, as well as on their level of integration (Veeneman, 2019; Tirachini, 2019). Consequently, assessing transport quality through a multimodal lens becomes a prerequisite for understanding how MaaS-oriented systems can deliver their promised benefits and avoid unintended effects such as modal displacement or reduced environmental quality.

Furthermore, Fig. 1 identifies the main *quality criteria* clustered according to the European standards for public transport service quality – EN 13816:2002 and EN 15140:2006. These standards establish eight core quality criteria that reflect both regulatory expectations and user-centred objectives commonly adopted in transport planning and service assessment (Barabino et al., 2013). Thus, the literature was examined by deepening the analysis of the quality criteria considered. The studies reveal a diverse yet converging set of criteria that capture both the functional and experiential aspects of urban mobility. They can be clustered into several interrelated domains, i.e., accessibility (A), availability (V), comfort (F), customer care (C), environmental impact (E), information (I), safety and security (S), and time (T), reflecting both user-oriented aspects and systemic conditions (CEN/TC 320, 2002; CEN/TC 320, 2006). Far from acting in isolation, these dimensions often intersect and reinforce one another, a dynamic that becomes particularly evident in multimodal contexts where users interact with multiple transport systems throughout a single journey. For instance, accessibility and availability criteria jointly influence the ease with which users can engage with a system: access to infrastructure, such as ramps for

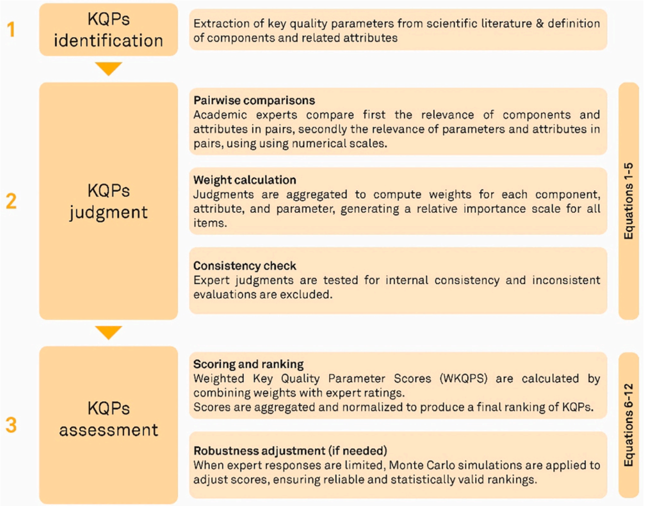


Source	Category	Transport mode	Quality aspect			Quality criteria							
			Service	S + I	Infrastructure	A	V	F	C	E	I	S	T
Hamerska et al. (2022)	1 e-micromobility	e-scooter	●				●	●	●			●	
Podciborski (2017)	6 public transport	tram			●	●		●			●	●	
Vujičić & Jasna (2019)		tram	●				●	●	●			●	●
Ely et al. (2012)		bus			●			●			●	●	
Barabino (2018)		bus			●	●		●	●		●	●	
Rosa & Da Cruz Lopes (2019)		bus			●	●	●	●			●	●	
Rossetti & Tiboni (2020)		bus			●	●	●	●			●	●	
Douglas (2015)	8 multimodal transport	bus + train		●		●		●	●	●	●	●	●
Talavera-Garcia & Soria-Lara (2015)		pedestrian mobility + bus stops			●		●	●			●	●	
Diana et al. (2016)		> 6 transport modes		●		●	●	●	●		●	●	●
Diana et al. (2017)		bus + pedestrian + cycling mobility		●		●	●	●	●		●	●	●
Groenendijk et al. (2018)		urban transit nodes		●				●	●				
D’Orso & Migliore et al. (2019)		pedestrian mobility + train stations			●			●				●	
Burlando et al. (2021)		bus + pedestrian mobility		●		●	●	●				●	
Chauhan et al. (2021)		multimodal transport hub		●		●	●	●	●	●	●	●	●
Hsu et al. (2018)	34 non-motorized mobility	bike-sharing	●			●	●	●	●		●	●	
Ma et al. (2019)		bike-sharing	●				●	●	●			●	
Liang et al. (2021)		bike-sharing	●				●	●	●			●	
Shin (2020)		bike-sharing	●			●	●	●	●				●
Julio et al. (2022)		bike-sharing	●				●	●	●				
Podgorniak-Krzykacz et al. (2022)		bike-sharing	●			●	●	●	●	●		●	
Xue et al. (2022)		bike-sharing	●				●	●	●	●		●	●
Hsu & Lin (2011)		cycling mobility			●			●				●	
Calvey et al. (2015)		cycling mobility			●		●	●		●	●	●	
Fistola et al. (2020)		cycling mobility			●			●			●	●	
de Aquino Traldi et al. (2022)		cycling mobility			●	●		●			●	●	
Sarker (2003)		pedestrian mobility			●		●	●		●			
Tan et al. (2007)		pedestrian mobility			●			●				●	
Amoroso et al. (2012)		pedestrian mobility			●	●	●	●		●		●	
Argin & Ozbil (2015)		pedestrian mobility			●			●			●	●	
Talavera-Garcia & Soria-Lara (2015)		pedestrian mobility			●		●	●			●	●	
Blečić et al. (2016)		pedestrian mobility			●			●				●	
Beura et al. (2017)		pedestrian mobility			●		●	●				●	
Soltani et al. (2017)		pedestrian mobility			●	●	●	●				●	
Bellizzi et al. (2019)		pedestrian mobility			●			●		●		●	
Larranaga et al. (2018)		pedestrian mobility			●			●				●	
Da Rocha et al. (2019)		pedestrian mobility			●	●		●				●	
Rowangould & Corning-Padilla (2019)		pedestrian mobility			●	●	●	●				●	
Sousa et al. (2019)		pedestrian mobility			●	●		●		●		●	
Arellana et al. (2019)		pedestrian mobility			●	●	●	●				●	
Ismail et al. (2020)		pedestrian mobility			●		●	●				●	●
Jahan et al. (2020)		pedestrian mobility			●			●				●	
Raswol (2020)		pedestrian mobility			●		●	●			●	●	
Rodriguez-Valencia et al. (2020)		pedestrian mobility			●	●	●	●		●		●	
Vallejo-Borda et al. (2020)		pedestrian mobility			●	●		●		●	●	●	
Bellizzi et al. (2021)		pedestrian mobility			●			●					
Ujjwal & Bandyopadhyaya (2021)		pedestrian mobility			●	●		●				●	
Du & Huang (2022)		pedestrian mobility			●		●	●				●	

A = accessibility
V = availability
F = comfort
C = customer care
E = environmental impact
I = information
S = safety & security
T = time

Fig. 1. Literature contributions on urban transport systems quality and quality aspects investigated. (See above-mentioned references for further information.)

passengers travelling with carriages or wheelchairs (Podciborski, 2017), or bike-sharing docking stations (Shin, 2020), and the spatial and temporal coverage of services (Julio et al., 2022; Liang et al., 2021; Arellana et al., 2019) are equally crucial in ensuring inclusive and reliable mobility. These basic conditions are closely linked to comfort-related factors, which extend beyond physical amenities to include the design of transport infrastructure (Sarkar, 2003; Argin and Ozbil, 2015; de Aquino Traldi et al., 2022), its integration and functionality in urban space (Amoroso et al., 2012), waiting environments (Ely et al., 2012; Vujičić and Jasna, 2019), and overall conditions such as cleanliness (Jahan et al., 2020; Ismail et al., 2020; Ujjwal and Bandyopadhyaya, 2021) and maintenance (Blečić et al., 2016; Raswol, 2020), as well as the presence of facilities, points of interest, and landscapes (Da Rocha et al., 2019). Simultaneously, the studies highlighted criteria related to the experience of users as the availability and quality of information, which are essential for planning in complex, multimodal settings (Rossetti and Tiboni, 2020; Podgorniak-Krzykacz et al., 2022), and by customer support systems that facilitate interaction with services, whether through digital platforms or human assistance, such as staff, ticketing, and user interfaces (Hsu et al., 2018; Ma et al., 2019; Xue et al., 2022). Safety and security underpin the perception of quality, spanning both protection from crashes (Tan et al., 2007; Beura et al., 2016; Larranaga et al., 2018; Bellizzi et al., 2021; Du and Huang, 2022) and crime (Soltani et al., 2017; Rowangould and Corning-Padilla, 2019; Bellizzi et al., 2019; Fistola et al., 2020). Time emerges as a cross-cutting criteria, integrating operational efficiency, such as frequency, reliability, and punctuality (Diana et al., 2016, 2017), with user experience, including walking time and adherence to schedules (Ismail et al., 2020). Differently, environmental impact, rather than reflecting the user's immediate experience, addresses the long-term consequences of mobility systems on air quality, land use, and natural resources. As such, it introduces a broader evaluative dimension that supports environmental sustainability-oriented transport planning (Calvey et al., 2015; Rodriguez-Valencia et al., 2020; Sousa et al., 2019; Podgorniak-Krzykacz et al., 2022).



Extraction of key quality parameters from scientific literature & definition of components and related attributes

Pairwise comparisons
Academic experts compare first the relevance of components and attributes in pairs, secondly the relevance of parameters and attributes in pairs, using using numerical scales.

Weight calculation
Judgments are aggregated to compute weights for each component, attribute, and parameter, generating a relative importance scale for all items.

Consistency check
Expert judgments are tested for internal consistency and inconsistent evaluations are excluded.

Scoring and ranking
Weighted Key Quality Parameter Scores (WKQPS) are calculated by combining weights with expert ratings.
Scores are aggregated and normalized to produce a final ranking of KQPs.

Robustness adjustment (if needed)
When expert responses are limited, Monte Carlo simulations are applied to adjust scores, ensuring reliable and statistically valid rankings.

Fig. 2. Simplified schematic overview of the methodology adopted for weighting, scoring, and selecting KQPs. The figure highlights the main procedural steps. .
Source: personal elaboration of authors

These quality criteria do not function independently but operate as an interconnected framework. In a multimodal system, the value of one parameter often depends on the performance of others: accessibility is meaningless without availability; comfort is undermined without safety; and sustainability goals require integration across infrastructure, land use, and service design. Recognising these interdependencies is essential for developing tools that help practitioners and policymakers assess, compare, and improve mobility options within increasingly complex urban environments.

Recent empirical studies on multimodal integration further highlight the complexity of user experience and operational performance in integrated transport systems, particularly in rapidly growing urban contexts. Research conducted in Indian cities, such as Bhopal, provides valuable evidence on how access-exit choices, connecting services, and service quality determinants influence multimodal travel behaviour. For example, studies based on factor analysis and structural equation modelling have shown that the perceived quality of service in multimodal public transport systems is strongly influenced by reliability, comfort, availability of information, and coordination between main and feeder modes (e.g., Tanwar & Agarwal, 2024; 2025a).

Complementarily, behavioural modelling approaches, such as multinomial probit and improved nested logit models, have shown that travellers' access and egress choices are highly sensitive to transfer times, connectivity and the availability of efficient connecting services (Tanwar & Agarwal, 2025c). These findings are reinforced by applied studies focusing on feeder service optimisation, which identify last-mile connectivity and service integration as critical enablers for accessible and attractive multimodal transport systems (Tanwar & Agarwal, 2025d).

On a broader scale, work on multimodal integration in India highlights both the opportunities and challenges associated with institutional coordination, policy alignment, and integration between infrastructures and services in the pursuit of sustainable urban mobility (Tanwar & Agarwal, 2025b). Overall, these empirical contributions emphasise that multimodal quality emerges from the interaction between infrastructure, service performance and user experience, rather than from individual components of the system considered in isolation.

They also underline the need for analytical approaches capable of jointly considering infrastructure-related and service-related dimensions when evaluating the quality of integrated urban transport systems.

As can be seen from this literature review, the topic of transport quality assessment is a broad and multifaceted field, characterised by a rich variety of criteria and parameters. However, despite the breadth of contributions reviewed, the current literature still highlights important gaps regarding the evaluation of transport quality from a multimodal and integrated perspective and the way transport quality is operationalised for multimodal planning practice.

First, most of the existing studies either focus on single transport

Table 1
Description of quality criteria.

Criteria	Description
Accessibility	It concerns access to the transport system, including its integration and interfaces with other modes of transport.
Availability	It describes the coverage of the transport system in relation to spatial distribution, operating times, service frequency, and modal options.
Comfort	It encompasses all features that contribute to making trips pleasant, relaxing, and enjoyable for passengers.
Customer care	It relates to service elements designed to ensure the closest feasible alignment between the standard service offered and individual user needs.
Environmental impact	It addresses the effects of the transport system on the surrounding environment.
Information	It refers to the structured provision of information that supports users in planning and carrying out their journeys.
Safety & Security	It refers to the sense of personal protection experienced by travellers.
Time	It covers all time-related aspects relevant to journey planning and execution.

Table 2
Components and attributes for assessing KQPs.

Components	Attributes	Description
Methodological quality	Measurability	The parameters should be measured in a theoretically valid and reliable way.
	Ease of availability	Data acquisition should be feasible at an acceptable cost, consistent with the budgetary constraints and efficiency requirements of PAs.
	Speed of availability	The evaluation process should allow for periodic updates, enabling shorter intervals between successive assessments.
	Interpretability	The use of clear and universally interpretable parameters should be pursued. Parameters expressed through numerical values, such as percentages, or simple categorical labels are preferred, as they are more intuitive and accessible for technicians, decision-makers, and end users.
	Relevance to multiple transport systems	The parameter should enable multiple transport systems to be simultaneously evaluated, rather than being measurable only for one system. The measurability of a parameter concerning multiple systems increases its effectiveness from a multimodal perspective.
Quality relevance	Integration between stakeholder and user perspectives	Assessing quality through the parameters should help shift the organisation toward a stronger user-centric approach. All stakeholders involved in the provision and management of transport services and infrastructure (e.g., local public transport providers – LPTPs, shared mobility service providers –SSPs, and PAs) should place users at the core of decision-making and give priority to their perspective.
	User-oriented	This represents a critical challenge in comprehensive quality evaluation: when multiple parameters are associated with a given quality dimension, it is essential to avoid parameters that are oriented toward LPTPs, SSPs, or PAs and are not easily interpretable by users. For example, in LPT, safety can be expressed through parameters that can readily recognized such as “the availability of accessible handrails”, rather than technical metrics like “injuries per kilometre”.
	Measurability from subjective and objective perspectives	Quality monitoring should be based on a balanced use of both subjective and objective data to ensure consistency. Combining subjective and objective parameters requires stakeholders responsible for the provision and management of transport services and infrastructure to evaluate how performance levels affect user satisfaction for each parameter, while also enabling the systematic collection of evidence on passengers’ perceptions of the delivered services and infrastructure.
	Quantification of the number of users	The parameter should incorporate a metric that reflects the number of users involved. The importance of this aspect is grounded in EN 13816:2002 and EN 15140:2006, which recommend expressing the degree of objective fulfilment—where feasible—as a proportion of affected transport users (CEN/TC 320, 2002; 2006).
	Relation between transport and public space qualities	The parameter allows us to measure aspects of both the quality of an urban transport system and the quality of public space. In this way, it can simultaneously provide assessments to support land use management and urban regeneration processes and improve the transport offer. For example, the presence of environmental facilities such as green spaces (parks, tree-lined streets, etc.) can be an aspect of transport quality that can promote active mobility; at the same time, it can be considered an aspect of public space quality, able to improve the perception of urban space and the management of land use and related environmental impacts.

Source: Authors' elaboration adapted from Castillo and Pitfield (2009), Barabino et al. (2020), Carrara et al. (2021), and Carra et al. (2022).

modes or analyse quality aspects in isolation without offering a systemic view that captures the interrelations across transport modes. Even when multimodal perspectives are adopted, the literature predominantly relies on extensive parameter lists, providing limited guidance on the relative importance, prioritisation, or trade-offs among quality parameters. As a result, practitioners and policymakers are often left without clear decision-support tools to identify which parameters should be prioritised when designing, monitoring, or improving multimodal urban transport systems. Second, to the best of our knowledge, studies that systematically weight and validate quality parameters across public transport, non-motorised mobility, and electric micromobility through structured expert judgement and multicriteria methods remain scarce.

This study aims to address these gaps by providing an integrated approach that moves beyond descriptive parameter sets and supports the identification of a reduced, prioritised, and internally consistent set of KQPs applicable across transport modes. This approach integrates a multimodal literature-based parameter identification with expert judgement, AHP weighting, and Monte Carlo-based robustness analysis, thus advancing the operational assessment of transport quality towards a more decision-oriented and practice-relevant approach.

3. Methodology

To facilitate the interpretation of the methodological process and to support readers in navigating the different analytical steps, Fig. 2 provides a simplified overview of the overall framework described in detail in Sections 3.1–3.3. This figure synthesises the identification of candidate parameters from the literature, the expert-based weighting of components and attributes using the AHP, and the subsequent assessment and selection of KQPs. This schematic representation is intended to complement the detailed methodological description and algebraic formulation presented below, offering a high-level perspective on the logical sequence of the proposed approach.

The methodology includes three phases and different steps to select a narrow but representative set of KQPs. The first phase, referred to as “KQPs identification”, derives an extensive set of candidate KQPs from the literature and defines the corresponding evaluation components and attributes. The second phase, “KQPs judgment”, engages academic experts to gather their assessments of components, attributes, and KQPs. The final phase, “KQPs assessment”, analyses the collected data to determine the most promising set of KQPs.

3.1. Phase 1: KQPs identification

Phase 1 aims to identify the most effective parameters for assessing the quality of a multimodal and sustainable urban transport system. This phase includes two steps.

The first step identifies a long list of KQPs from a literature review. To structure it and ensure that all the most relevant quality aspects are included, the long list of KQPs is organised using the service quality norms EN 13816:2002 (CEN/TC 320 2002) and EN 15140:2006 (CEN/TC 320 2006) as a prior reference. Although these standards were originally developed to monitor the quality of service provided by public transport companies, adopting a structured classification based on recognised norms guarantees methodological consistency, transparency, and possible comparability of results. In this way, the criteria defined in these norms are adapted to be applicable to multimodal systems (Table 1). Based on this framework, each parameter of the long list will be clustered into eight macro-criteria. However, their relevance varies across transport systems, and their effectiveness in capturing the multimodal dimension is therefore uneven. In the best cases, a parameter applies to all, or at least three out of four transport systems considered; in the worst cases, it covers only one or two.

The second step defines components and attributes to evaluate the relevance of quality parameters (Table 2). It considers the methodological quality of KQPs and their relevance in comparison to multimodal transport quality as components. The choice of these two components stems from the dual nature of this study’s challenge in selecting effective quality parameters. On one hand, parameters must be technically sound and usable within planning and decision-support processes, which requires clarity, measurability, and reliability; hence, the focus on methodological quality. On the other hand, as the objective of this research is to define and assess the quality of multimodal transport systems, it is essential that each parameter meaningfully captures the aspects that shape users’ experiences and influence urban mobility dynamics. For this reason, we included quality relevance as a specific evaluation component. Together, these components ensure a balanced evaluation of each KQP, capturing both its operational feasibility and its significance in representing the quality of a multimodal transport system.

Despite these components are aimed at identifying the main characteristics of KQPs, they are not specific enough to drive the selection of KQPs. For this reason, they are structured into different and more accurate attributes. Each attribute may have a specific level of importance that may vary to reflect different perspectives, although the components and related attributes are general and arise from KQPs considered as SMART, i.e., Specific, Measurable, Achievable, Realistic, and Timely (Doran, 1981).

As for the methodological quality, as suggested by Castillo and Pitfield (2009), we include the attributes of measurability, interpretability, speed, and easy availability. However, we add a fifth attribute that is critical for this research. It concerns the relevance of parameters to the assessment of a multimodal transport system. This attribute is crucial because the quality is evaluated across the entire travel experience, rather than just focusing on the journey with a specific service. This highlights the importance of considering every stage of the travel experience, from gathering pre-trip information to the final leg of the journey to the destination (Diana et al., 2016).

As for quality relevance, as suggested by Barabino and Di Francesco (2016), we include the attributes of integration between stakeholder and user perspectives, user orientation, measurability from both subjective and objective perspectives, and quantification of the number of users. Also in this case, we add a fifth attribute that is crucial to converge transport planning and urban planning, which concerns the relation between transport and public space qualities. Indeed, the concept of quality cannot be limited to the transport mode but must be related to everything that interacts with it. Indeed, aspects of urban space can have a strong weight in influencing the travel mode choices of users. The absence of lighting, for example, can compromise users' perception of the security of a pedestrian or cycle route. Similarly, the presence of greenery or attractiveness can increase the perceived comfort of the route, favouring its choice.

Table 2 defines each component and attribute.

3.2. Phase 2: KQPs judgment

Phase two involves academic experts driving the selection of KQPs. The decision to involve only academic experts, rather than administrators or other stakeholders, is driven by the specific objectives of this phase. Academic experts provide a research-based, and multidisciplinary perspective grounded in theoretical frameworks and comparative international experiences. Their role is to critically evaluate the conceptual validity and methodological robustness of the quality parameters. While administrators offer valuable operational and contextual knowledge, their views may vary significantly depending on local policies and constraints, which could introduce biases not aligned with the aim of defining a universally applicable set of KQPs. Future research phases may involve other stakeholder groups to complement and validate these findings in practical contexts.

Academic experts are asked to assess components, attributes, and parameters. There are many methods for engaging academic experts, such as Contingent Field Survey (Blečić et al., 2016), Field and face-to-face Survey (Argin and Ozbil, 2015), Random Intercept Surveys

(Rodriguez-Valencia et al., 2020). However, no single approach is universally applicable or accepted. In this case, a web survey, which is structured using the PHP language, is chosen because it allows for reaching many international academic experts at low operating costs, such as interview time, data coding, and data processing. Additionally, a web survey is non-intrusive and requires less effort from respondents.

Parallelly, measuring the relevance of components and related attributes is a complex task that requires an in-depth knowledge of the subject. Lacking technical knowledge, transport users and travellers were not directly considered here, even though their perspective is a priority in this research. Their perspective will become crucial in assessing the desired quality of the parameters selected using the proposed approach.

Involved academic experts emerged from academia and literature review and include university professors and researchers working on the topics of mobility and quality assessment of urban transport systems. Because the research investigates a multimodal dimension, academic experts in different fields of transportation were involved: pedestrian mobility, cycling, public transport, and micromobility. However, this heterogeneity may lead to evaluations conditioned by specific cultural and technical backgrounds that are not always multimodality-oriented, potentially resulting in biased assessments or inconsistent values.

To objectively assess the relevance of components and related attributes, we apply a weighting process, thereby minimising the likelihood that the number of academic expert judgments would also increase the possibility of receiving biased opinions. According to Zelany (1974) and Castillo and Pitfield (2009), weights can be directly assigned by asking experts to express their preferences for individual items. However, this approach may be problematic, as humans often struggle to translate complex information into consistent weights when faced with numerous items. Moreover, other approaches could be adopted (e.g., Wang and Lee, 2009). Nonetheless, the proposed approach incorporates the AHP, which helps reduce potential bias by deriving weights through pairwise comparisons of criteria and producing ratio-scale priorities for each comparison set, thereby addressing inconsistencies in expert judgments (Saaty, 1977, 1987, 1990, 1994; Wind & Saaty, 1980).[1]

Specifically, in this study, the AHP procedure consists of four main steps. First, each expert expresses relative preferences between pairs of components or attributes through a pairwise comparison matrix. Second, these judgments are transformed into a weight vector by computing the geometric mean of the comparisons for each component, which allows the aggregation of relative preferences while preserving their ratio-scale properties. The resulting weights are then normalized so that they sum to one and can be meaningfully compared across attributes. Third, a consistency check is performed by estimating the maximum eigenvalue of each comparison matrix, which measures the degree to which the expert's judgments are logically coherent. Finally, the consistency index and the consistency ratio are computed to verify whether the level of inconsistency remains within acceptable thresholds; only judgments meeting this criterion are retained. The overall approach is particularly effective in resolving disagreements among academic experts with potentially differing viewpoints.

To be more formal, let:

- S be the set of components or attributes;
- J be the set of academic experts involved;
- $v_{sq,j}$ be the numerical judgment provided by academic expert j ∈ J of the pairwise comparison between pair of components or attributes s ∈ S and q ∈ S;
- V_{sj} be the overall un-normalised weight of component or attribute s ∈ S returned by academic expert j ∈ J;
- CI_j be the consistency index provided by academic expert j ∈ J and assesses whether the judgments are consistent with the choices reported in the survey;
- $\lambda_{max,j}$ be the maximum eigenvalue required for computing the measure of consistency by academic expert j ∈ J;
- RCI be the random consistency index, which represents a CI function tabulated based on the maximum number of quality components or attributes (Wind and Saaty, 1980).

A four-step algorithm was used to calculate the weights and conduct a consistency check on the judgments.

For each academic expert j ∈ J:

1. Create the matrix of pairwise comparison V_j between components or attributes for each academic expert j ∈ J;
2. Calculate V_s and v_s from this matrix. Specifically, the calculation of the weight vector V_s is made as follows (among the different methods):

$$V_{sj} = \sqrt[s]{\prod_{s \in S} \frac{v_{sq,j}}{v_{qs,j}}} \quad \forall j \in \mathrm{J} \tag{1}$$

Next, V_s is normalised as follows:

$$v_{sj} = \frac{V_{sj}}{\sum_{s \in S} v_{sqj}} \quad \forall j \in \mathrm{J} \tag{2}$$

3. Check the consistency, computing λ_{max} as follow:

$$\lambda_{max,j} = \frac{\sum_{q \in S} \left[\frac{\sum_{s \in S} \left(\frac{v_{sqj}}{v_{qsj}} * v_{sqj} \right)}{v_{qj}} \right]}{|S|} \quad \forall j \in \mathrm{J} \tag{3}$$

4. Check if $\lambda_{max,j} \geq |S|$ and compute CI_j, as follows:

$$CI_j = \frac{(\lambda_{max,j} - |S|)}{(|S| - 1)} \quad \forall j \in \mathrm{J} \tag{4}$$

where the assessments exhibit perfect consistency if $\lambda_{max,j} = |S|$, thus $CI_j = 0$.

Finally, compute RCI as follows:

$$CRI_j = \frac{CI_j}{RCI} \quad \forall j \in \mathrm{J} \tag{5}$$

Pairwise comparisons are considered trustworthy when the CRI ≤ is 0.1 or when expert judgments demonstrate coherence and align with the survey responses. If the CRI is > 0.1, experts are asked to revise their evaluations due to the inconsistency in their judgments. Detailed guidance on the application of the AHP is provided in Saaty's publications (e.g., Saaty, 1987; 1994).

For each expert j ∈ J, separate matrices are developed at the component or attribute levels. Experts whose judgments do not satisfy the required consistency threshold are excluded from the analysis. The final weights are calculated by averaging the weights derived from all consistent expert inputs. These last weights are established for each component and attributes and serve as inputs for the following step.

In this study, the AHP is applied twice: first, academic experts compare the two quality components, and, next, the two sets of five attributes characterizing each component. They adopt a numerical scale from 1 to 9.

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[1] Although the method has been subject to criticism (Dyer, 1990), numerous scholars have supported its application and highlighted the benefits associated with its use (e.g., Harker and Vargas, 1990; Saaty, 1990; Forman and Gass, 2001; Ramanathan, 2001; Millet and Wedley, 2002; Macharis et al., 2004; Oguztimur, 2011). Furthermore, the Analytic Hierarchy Process (AHP) is widely employed across various engineering disciplines, which has further encouraged its adoption among bus operators (e.g., de Steiguer et al., 2003).

Next, academic experts rate each KQP against all the attributes according to predefined scales. In this case, we use a shorter numerical (Likert) scale from 1 (the worst) to 5 (the best). Compared to the first phase, the second one took longer for academic experts to assign values to the long list of parameters derived from the literature across the 10 quality attributes. So as not to discourage academic experts from contributing to the survey and trying to get more responses, the range was reduced from 1 to 9 to 1–5. The narrower range in the second stage of the survey made it easier for academic experts to evaluate, as it sped up the judgment process by reducing the number of nuances to consider.

3.3. Phase 3: KPQs assessment

This stage processes the data collected from the academic experts and produces the final score for each KQP. This score is defined as the Weighted Key Quality Parameter Score (WKQPS) and is obtained from an additive weighting, which aggregates weights and outcome marks to evaluate the performance of each KQP. Specific steps characterised this phase, as shown below and mined from Barabino et al. (2020). To be more formal, let:

- P be the set of KQPs;
- m_j be the AHP-derived weight assigned to the methodological quality component by academic expert $j \in J$;
- q_j be the AHP-derived weight of the quality relevance component as evaluated by academic expert $j \in J$;
- w_{jh} be the AHP-derived weight of attribute $h \in H$ as evaluated by academic expert $j \in J$;
- w_{jk} be the AHP-derived weight of attribute $k \in K$ as evaluated by academic expert $j \in J$;
- $\underline{M}$ be the average weight of the methodological quality component;
- $\underline{Q}$ be the average weight of the quality relevance component;
- $\underline{w_h}$ be the average weight of attribute $h \in H$;
- $\underline{w_k}$ be the average weight of attribute $k \in K$;
- V_{pjh} be the score assigned to parameter $p \in P$ for attribute $h \in H$ by academic expert $j \in J$;
- V_{pjk} be the score assigned to parameter $p \in P$ for attribute $k \in K$ by academic expert $j \in J$;
- $\underline{V_{ph}}$ be the average score of parameter $p \in P$ for attribute $h \in H$;
- $\underline{V_{pk}}$ be the average score of parameter $p \in P$ for attribute $k \in K$.

For each parameter p, the WKQPS is calculated using the following four-step algorithm.

1. Compute $\underline{M}$ and $\underline{Q}$

$$\underline{M} = \frac{\sum_{j\in J} m_j}{|J|} \tag{6}$$

$$\underline{Q} = \frac{\sum_{j\in J} q_j}{|J|} \tag{7}$$

2. Compute $\underline{w_h}$ and $\underline{w_k}$

$$\underline{w_h} = \frac{\sum_{j\in J} w_{jh}}{|J|} \quad \forall h \in H \tag{8}$$

$$\underline{w_k} = \frac{\sum_{j\in J} w_{jk}}{|J|} \quad \forall k \in K \tag{9}$$

3. Compute $\underline{V_{ph}}$ and $\underline{V_{pk}}$

$$\underline{V_{ph}} = \sum_{j \in J} \frac{V_{pjh}}{|J|} \quad \forall h \in H; \forall p \in P \tag{10}$$

$$\underline{V_{pk}} = \sum_{j \in J} \frac{V_{pjk}}{|J|} \quad \forall h \in H; \forall p \in P \tag{11}$$

4. Compute WKQPS_p

$$WKQPSp = \underline{M} \bullet \left(\sum_{h \in H} \underline{w_h} \bullet \underline{V_{ph}}\right) + \underline{Q} \bullet \left(\sum_{k \in K} \underline{w_k} \bullet \underline{V_{pk}}\right) \quad \forall p \in P \tag{12}$$

Lastly, we determined the final set of KQPs by sorting the list in descending order of WKPQS, where the best parameters correspond to their highest estimated values.

To select the final set of KQPs, quartile-based thresholds were adopted as a transparent and non-parametric filtering criterion to reduce the initial set of parameters while preserving those consistently rated as highly relevant across experts. This choice avoids arbitrary numerical cut-offs and is commonly used in exploratory multi-criteria screening when no *a priori* threshold can be justified.

Hence, the first quartile of the distribution of WKPQS values of the overall set of parameters is chosen, considering the highest-ranked KQPs relevant for the quality management of multimodal and sustainable transport systems in urban areas. The first quartile is a reasonable way to provide an adequate assessment of the quality of an urban transport system because:

- it is not excessively high, so it does not require excessive efforts in terms of time and resources;
- it is not excessively low, so it is not in danger of being unrepresentative and does not oversimplify a very complex system.

Next, the parameters higher up the list were supplemented and adjusted to meet explicit conceptual selection criteria, ensuring the final set is balanced and multimodally representative. As a result, the following selection criteria were applied:

- at least one parameter for each of the 8 criteria derived from standards EN 13816:2002 (CEN/TC 320 2002) and EN 15140:2006 (CEN/TC 320 2006) must be present in the final set;
- each parameter must be able to measure at least three of the four transport categories included in the study (public transport, pedestrian mobility, bicycle mobility, and electric micromobility), in the final set. This criterion was chosen to obtain a set that is as applicable as possible to a multimodal transport system.

These coverage rules ensure that the final set of KQPs adequately represents the multidimensional nature of multimodal transport quality, avoiding dominance by a single mode or criterion. In a limited number of cases, manual substitutions were introduced when purely rank-based selection would have excluded parameters necessary for conceptual completeness and multimodal balance. Importantly, these substitutions did not involve the introduction of low-ranked or marginal parameters; instead, they were drawn from parameters that were already highly positioned in the overall ranking. These substitutions were guided by explicit planning-related considerations and are fully documented to maintain transparency and replicability.

For instance, parameters that achieve high scores in the ranking but are intrinsically mode-specific should be excluded from the final KQP set, as they do not support a genuinely multimodal assessment. This applies, for instance, to parameters such as “Seating and personal space for public transport vehicles at boarding and alighting points”, which, although highly relevant for evaluating public transport services, cannot be meaningfully extended to pedestrian mobility, cycling, or micromobility. Similarly, if a purely rank-based selection were to exclude all parameters related to a specific criterion (e.g., Information or Customer Care), such an outcome would lead to an incomplete representation of transport quality. In such cases, a parameter representative of the missing criterion should be included, even if its score lies just below the quantitative threshold.

Finally, the proposed methodology includes a final uncertainty condition to address potential limitations in the sample size obtained

Table 3
Long list of criteria and parameters for the assessment of transport quality in the urban environment.

Criteria	Parameter – level I	Parameter – level II	Public Transport	Pedestrian mobility	Cycling mobility	Micro-mobility
Time	Adherence to schedule / Reliability	Efficiency	●			
		Punctuality	●			
		Regularity	●			
	Length of trip time	At Origin/boarding and alighting/boarding and alighting/Destination points	●	●	●	●
		Time in-vehicle	●		●	●
		Time for trip planning	●		●	●
Safety & Security	Emergency management	Facilities and plans	●	●	●	●
	Freedom from accident	Crashes	●	●	●	●
		Avoidance/visibility of hazards	●		●	●
		Travel behaviour	●			
		Presence/visibility of supports, e.g., handrails	●	●	●	●
		Preventive design	●	●	●	●
		Speed	●	●	●	●
		Traffic flow	●	●	●	●
	Freedom from crime	Lighting	●	●	●	●
		People (mis)behaviour	●	●	●	●
		Public safety monitoring	●	●	●	●
Information	General information	About accessibility	●	●	●	●
		About availability	●	●	●	●
		About security	●	●	●	●
		About source of information	●	●	●	●
		About time	●			
		About comfort	●		●	●
		About environmental impact	●		●	●
		About customer care	●		●	●
Environmental impact	Pollution and health	Exhaust	●	●	●	●
		Natural resources	●	●	●	●
Customer care	Assistance	Customer orientation	●		●	●
	Commitment	Innovation and initiative	●		●	●
	Customer interface	Complaints	●		●	●
		Tools and related qualities	●		●	●
	Staff	Staff appearance	●			
		Staff availability	●			
		Staff skills (behaviour)	●		●	●
	Ticketing options	Fare structure and policy	●		●	●
		Consistent price calculations	●		●	●
Comfort	Ambient conditions	Atmosphere	●	●	●	●
		Cleanliness	●	●	●	●
		Disruption	●	●	●	●
		Density		●	●	●
		Visual pollution	●	●	●	●
		Odour	●	●	●	●
		Noise	●	●	●	●
		Weather protection	●	●	●	●
	Complementary facilities	Commercial activities and services	●	●	●	●
		Environment facilities	●	●	●	●
		Entertainment	●			
		Amenities	●	●	●	●
	Ergonomics	Ease of movement			●	●
		Furniture design	●	●	●	●
	Ride comfort	Driving	●			
	Path comfort	Walking and cycling		●	●	●
	Seating and personal space for public transport vehicles	In-vehicle	●			
		At b/a points	●	●		
Availability	Network	Modes	●	●	●	●
		Area covered	●	●	●	●
		Distance to O/D points	●	●	●	●
	Operation	Frequency	●			
		Operating hours	●			
		Load factor	●		●	●
Accessibility	External interface	Interchange/multimodality	●	●	●	●
	Internal interface	Entrance/exits	●	●	●	●
		Internal movement	●	●	●	●
	Ticketing availability	Ticketing acquisition	●		●	●
		Ticketing validation	●			

from the web-based survey (if any). Specifically, if the number of expert responses is sufficiently large and balanced, the final set of KQPs is selected based on the first quartile of the WKQPS distribution. However, when the number of responses is relatively low, an adjustment of the values of the WKQPS is introduced to ensure the robustness of the results and to mitigate coverage bias.

The adjustment of values of the WKQPS may become necessary because web surveys, while efficient and scalable, are particularly prone to bias when the respondent pool is limited in size or composition (Dever et al., 2008). This bias can distort the aggregated evaluations and affect the reliability of parameter ranking. To overcome this limitation, we apply Monte Carlo simulation, as previously done in similar works on transit service quality (Barabino et al., 2020) and electric charging infrastructure (Carra et al., 2022) and other (Castillo and Pitfield, 2009. In this context, the deterministic evaluation model, based on actual expert scores, is converted into a stochastic model. A set of random numbers is generated and used as input in an iterative process that simulates the full computation of WKQPS, producing an Adjusted WKQPS (AWKQPS). This procedure is repeated several times to generate a simulated data distribution that reflects the same structure as the expert responses. A probability distribution is chosen to represent the available knowledge, and the final ranking is obtained by reapplying the evaluation model to the simulated data. Through this step, the methodology not only increases the robustness of the final selection but also enhances its reliability in scenarios where expert participation is limited, ensuring that the selected KQPs maintain statistical validity and conceptual soundness.

4. Results

4.1. Phase 1: KQPs identification

According to the first phase of the method, the long list of KQPs for a multimodal urban transport system has been derived from the systematic literature review (Ferretto et al., 2024). Moreover, this list was clustered according to eight readjusted criteria from the service quality standards EN 13816:2002 (CEN/TC 320 2002) and EN 15140:2006 (CEN/TC 320 2006). The long list of KQPs is structured into different levels of parameters. The first level comprises 23 parameters and represents a specification of individual criteria; it becomes even more detailed with the second-level parameters, which includes 65 quality parameters (Table 3), which academic experts subsequently evaluate.

It is important to note that these parameters have been standardised in terms of terminology, consolidating those expressed differently across different papers but with the same meaning. Therefore, in the papers they come from, parameters might be called slightly differently and not necessarily related to the eight quality criteria.

Each parameter was then associated first with a quality criterion derived from quality-of-service evaluation methodologies, then with one or more transport systems that it can potentially evaluate.

Generally, the results are clearly holistic, aiming to enhance an urban mobility system that is multidimensional and user-centred.

4.2. Phase 2: KQPs judgment

In phase 2, academic expert judgment on the quality of components, attributes, and parameters was elicited through a web-based international survey titled “*Research on Key Quality Parameters of an Integrated and Sustainable Urban Transportation System*”. The targeted panel consisted of academic experts identified through a systematic literature review, complemented by additional professors and researchers known to be actively engaged in research on transportation. This selection approach ensured that the respondents had proven technical and research experience across the full spectrum of the topic, including public transport, non-motorised mobility, and micromobility. Therefore, all authors cited in Fig. 1 were contacted as their academic background and domain knowledge made them suitable to assess the KQPs investigated in the study.

To support the validity of the survey, all questions were pre-tested and piloted before full deployment. Additionally, detailed explanations of the research framework, components, and attributes were provided within the survey to mitigate misunderstandings and reduce potential bias. The clarity of the material, combined with the academic background of participants, further supports the reliability of the collected judgments.

The web survey was structured into two parts. In the first part, they were given two first-level components and asked to indicate which one they considered relevant and to what extent, choosing a value to show the strength of their preference through a pairwise comparison (Appendix A, Fig. A.1). Then, as with the first question, they were asked to indicate attributes they considered relevant and to what extent (Appendix A, Fig. A.2).

They compared the two components of Methodological Quality and Quality Relevance and the related ten attributes, according to a 1–9-point Saaty scale, where:

- 1 indicates equal importance between the compared elements;
- 3 denotes moderate importance, where one element is slightly preferred over the other;
- 5 reflects strong importance, with a clear preference for one element;
- 7 corresponds to very strong importance, where one element is significantly favoured over the other;
- 9 expresses extreme importance, indicating the maximum possible preference of one element;
- 2, 4, 6, and 8 are intermediate values among the defined levels and are used when judgments fall between two adjacent degrees of importance.

In the second part, experts were asked to rate each parameter on a 1-to-5 scale, assigning a value to each attribute for each parameter of the original list of KQPs (Appendix A, Fig. A.3).

The full survey required three waves of data collection that were carried out between June and October 2024. For the first part, the survey was sent via email to 258 recipients across 34 countries, with 220 successful deliveries (85%) and a total of 27 complete responses collected during the first wave (response rate of 12%). A reminder was sent two weeks after the first wave, and with the second wave, another 18 responses were obtained, for a total of 45 (response rate of 20%).

While this rate may appear modest, it is consistent with typical response rates in similar academic expert surveys, especially in niche fields (Barabino et al., 2020). This is also in line with the results reported by Sivo et al. (2006), who analysed response rates in web-based surveys across six leading information systems journals.

All respondents possessed recognized expertise in the quality assessment of one of the mobility types considered, ensuring the relevance and quality of their input. Of the respondents, 67% were European (including Italy, Netherlands, UK, Spain, Portugal, Belgium, Greece, and Croatia), 17% were from North and South America, and 11% were from Asia. While responses were concentrated mainly in Europe, this is influenced by the panel of studies selected, which guided the

Table 4
Composition of the Sample and Survey Participation Rates.

Country	Phase 1: waves 1 and 2			
	Email sent	*Email delivered*	*Responses received*	*Response rate (%)*
Europe	145	122	33	27
North & South America	47	45	7	16
Asia	62	50	5	10
Oceania	4	3	0	0
Total	**258**	**220**	**45**	**20**

Table 5
Average weights of the components and attributes.

Components	Aggregate average weight (μ)	Standard deviation (σ)	Coefficient of variation % (σ/μ)
Methodological quality	0.513	0.260	50.8
Quality relevance	0.487	0.267	54.8
Methodological quality attributes			
Measurability	0.262	0.099	37.8
Easy Availability	0.200	0.128	64.1
Speed Availability	0.090	0.033	36.2
Interpretability	0.231	0.1093	40.1
Relevance to multiple transport systems	0.218	0.130	59.6
Quality relevance attributes			
Integration between stakeholder and user perspectives	0.147	0.098	66.5
User-orientation	0.193	0.112	58.3
Measurability from subjective and objective perspectives	0.170	0.091	53.6
Quantification of the number of users	0.208	0.124	59.4
Relation between transport and public space qualities	0.282	0.117	41.5

identification of experts. Specifically, the comparison between the panel and respondent distributions shows coherence for North and South America, a slight overrepresentation for Europe, and an underrepresentation for Asia. Nevertheless, this distribution reflects the geographical composition of the literature-based expert panel from which participants were identified, rather than an *a priori* regional focus of the study.

Table 4 provides an overview of the distribution of email invitations, deliveries, and responses by continent.

To ensure a timely progression of the research and to deepen the analysis, the second part of the survey (the third wave) was distributed in October 2024 to a selected group of academic experts with specialized knowledge of the topic. This targeted approach facilitated more direct engagement with high-quality and consistent feedback that contributed to the robustness of the findings.

Next, the judgments of academic experts were analysed. They were disaggregated and systematized using a matrix system in Excel, where each academic expert (identified by an ID number) was associated with one matrix (Appendix B, Figs. B.1 and B.2).

Thus, the AHP has been applied to calculate the weights of components and attributes, and their average according to the Eqns. 1–5. In analysing evaluations of the pairwise comparisons between the attributes, only four evaluations with consistency values strongly above 0.1 (thus, inconsistent) were deleted. Indeed, these were probably ratings made without substantial criteria. Therefore, all 45 judgments were retained for the pairwise comparison of the components, while the original ratings decreased from 45 to 41 for the pairwise comparison of the attributes.

Then, Eqns. 6–12 were applied to obtain the WKQPS. The average weight (μ), standard deviation (σ), and coefficient of variation (σ/μ) of components and attributes are presented in Table 5. While the standard deviation (σ) values are almost the same for the Methodological quality and Quality relevance, the aggregate average weight (μ) values differ slightly, showing a preference for the Methodological quality. However, the coefficient of variation (σ/μ) is higher for the Quality relevance and shows a slight spread among the responses, likely due to greater subjective interpretation and contextual influence, which might depend on local priorities, project objectives, and disciplinary perspectives.

Academic experts considered Interpretability ($\mu \approx 0.231$) and Measurability ($\mu \approx 0.262$) as the most relevant attributes of Methodological quality, suggesting a preference for parameters that allow robust, objective assessment. In contrast, the Easy Availability and Speed Availability showed variability that highlights context-specific influences, i.e., contexts with accessible data vs. those with informational constraints. Within the attributes of Quality relevance, the most relevant ones were the relation between transport and public space qualities ($\mu \approx 0.282$) and the quantification of the number of users ($\mu \approx 0.208$). These results highlight the high value of functional urban integration and tangible usage metrics. In contrast, the lower weight of the Integration between stakeholder and user perspectives ($\mu \approx 0.147$) and high variability (66.5%) may reflect the differing institutional practices or difficulties coordinating multi-actor perspectives. Medium values characterise the User-orientation ($\mu \approx 0.193$) and Measurability from subjective and objective perspectives ($\mu \approx 0.170$).

4.3. Phase 3: KQPs assessment

In phase 3, a first WKQPS is obtained by additive weighting, aggregating the outcome weights and scores to evaluate the performance of each KQP, and providing a preliminary selection of the most promising KQPs. However, since the sample of responses to the web survey was small, a probability of bias was admitted. Therefore, the Monte Carlo simulation was applied to mitigate it. This technique permits the production of artificial data that needs to be matched with the observed data based on academic expert judgments, deriving the Adjusted Weighted Key Quality Parameter Score (AWKQPS) for each KQP. The Monte Carlo simulation is implemented as a robustness-enhancing procedure rather than as a full probabilistic model. The simulated values are generated assuming independence among quality parameters and attributes.

In this study, the Monte Carlo simulation is applied to the set of KQPs related to each attribute. Specifically, for each attribute, the probability distribution is constructed to directly reflect the empirical distribution of the judgments provided by the experts. This is achieved through repeated random sampling within the original [1–5] evaluation scale, without imposing any additional parametric assumptions, so that the resulting distribution faithfully represents the current state and variability of expert opinions. The observed distribution of the marks given by academic experts is simulated 1,000 times for each attribute (thus 10,000 times for each parameter). Preliminary sensitivity tests showed that further increasing the number of simulations did not lead to meaningful changes in the resulting rankings, indicating that the simulation size was sufficient and that the outcomes had reached convergence and stability. The score of each parameter (based on 650,000+ Monte Carlo simulations) was computed by applying Eqn. (12), which returned the final scores for each parameter. Fig. 3 shows the two scores, i.e., WKPQS and AWKPQS as well their variation for each for the parameters belonging to the first quartile, plus the parameters with the highest scores belonging to the criteria missing from the ranking. The complete version with all 65 parameters is provided in Appendix C, Table C.1., following the descending order of the AWKPQS. The comparison between WKQPS and AWKQPS further confirmed that the relative ordering of the most relevant KQPs remains largely consistent, suggesting limited sensitivity of the final rankings to stochastic perturbations of the expert judgments.

As can be seen from the selection of the total AWKPQS, in the first quartile, there are no parameters that belong to the criteria of Information, Customer care, and Environmental impact. Then, a parameter for each of these three criteria was added, choosing those with the highest value in the total score. Specifically, the parameters of About accessibility, Complaints, and Natural resources were added. At this point, the final set of KQPs consists of 19 quality parameters. However, not all of them can evaluate at least three out of four transport systems included in the research (See Tab. 4). Specifically, five parameters in the first quartile do not meet this selection criterion and were replaced with

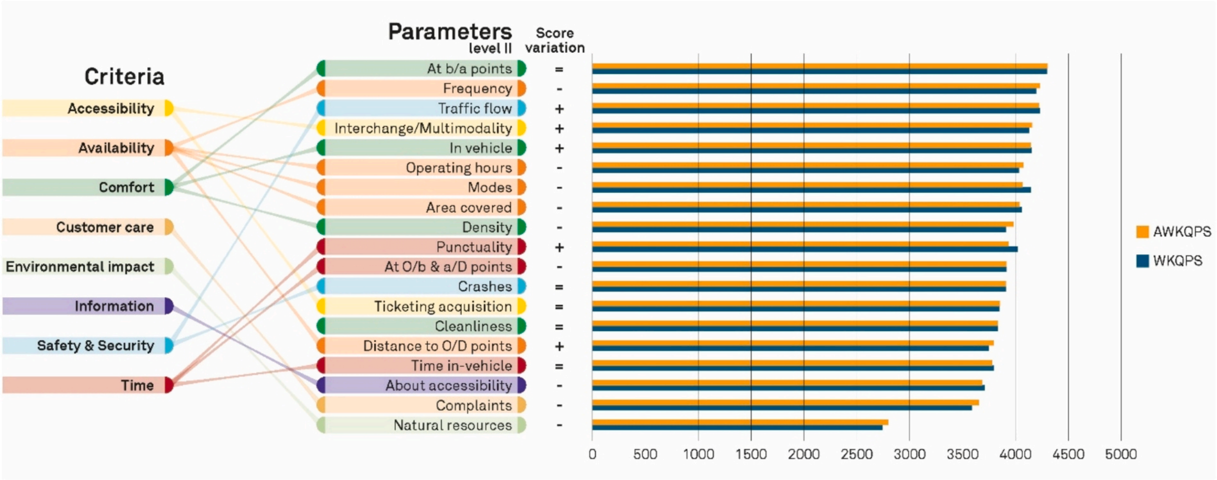

Fig. 3. Comparison between the AWKQPS and WKQPS variation for the parameters belonging to the first quartile plus the parameters with the highest scores belonging to the criteria missing from the ranking (i.e., Customer care, Environmental impact, Time).

Table 6
Final selection of KQPs following the order of the AWKPQS.

N	Criteria	Parameter I	Parameter II	Public Transport	Pedestrian mobility	Cycling mobility	Micro-mobility
1	Safety & Security	Freedom from accident	Traffic flow	●	●	●	●
2	Accessibility	External interface	Interchange / multimodality	●	●	●	●
3	Availability	Network	Modes	●	●	●	●
4	Availability	Network	Area covered	●	●	●	●
5	Comfort	Ambient conditions	Density	○	●	●	●
6	Time	Length of trip time	At Origin/boarding and alighting/ Destination points	●	●	●	●
7	Safety & Security	Freedom from accident	Crashes	●	●	●	●
8	Accessibility	Ticketing availability	Ticketing acquisition	●	○	●	●
9	Comfort	Ambient conditions	Cleanliness	●	●	●	●
10	Availability	Network	Distance to O/D points	●	●	●	●
11	Time	Length of trip time	Time in-vehicle	●	○	●	●
12	Safety & Security	Freedom from crime	Lighting	●	●	●	●
13	Safety & Security	Freedom from accident	Speed	●	●	●	●
14	Accessibility	Internal interface	Entrance/exits	●	●	●	●
15	Availability	Operation	Load factor	●	○	●	●
16	Comfort	Complementary facilities	Amenities	●	●	●	●
17	Information	General information	About accessibility	●	●	●	●
18	Customer care	Customer interface	Complaints	●	○	●	●
19	Environmental impact	Pollution and health	Natural resources	●	●	●	●

five other parameters with the highest value in the total score. The parameters replaced are: At b/a points, Frequency, In-vehicle, Operating hours, and Punctuality. Table 6 shows the final selection of KQPs.

5. Discussions

Table 6 shows that among the parameters belonging to the first quartile of the complete list, there is practically no difference between WKPQS and the AWKPQS, which share 15 of 16 KQPs. The Monte Carlo simulation enhanced the scores of each parameter without altering their relative importance, though the adjustment of the original scores led to minor changes in the ranking of some parameters.

In addition, while the AHP and Monte Carlo simulation have been widely applied in decision-making contexts, the novelty of the present framework lies in their integrated application for multimodal transport quality assessment. By combining expert weighting (AHP) with probabilistic robustness analysis (Monte Carlo), the methodology explicitly addresses two common challenges: the limited size and potential bias of expert samples, and the uncertainty inherent in subjective judgments. This integrated procedure enables the selection of a prioritised, context-sensitive set of KQPs, rather than relying on exhaustive lists of parameters. Moreover, the subsequent filtering and adjustment process ensures that the final KQPs: (i) cover all core quality criteria relevant to multimodal transport, (ii) remain applicable across multiple transport modes, and (iii) balance infrastructure-focused and user-oriented aspects of quality. Together, these features highlight the framework's capacity to provide decision-oriented insights, supporting planners in identifying critical intervention points and facilitating evidence-based, multimodal transport planning.

Dwelling on the first quartile, the most important quality criteria are Safety and Security, and Availability, followed by Comfort, Accessibility, and Time. In contrast, Customer Service, Information, and Environmental Impact are considered less important. The most relevant criteria of Safety and Security, Availability, Comfort, Accessibility, and

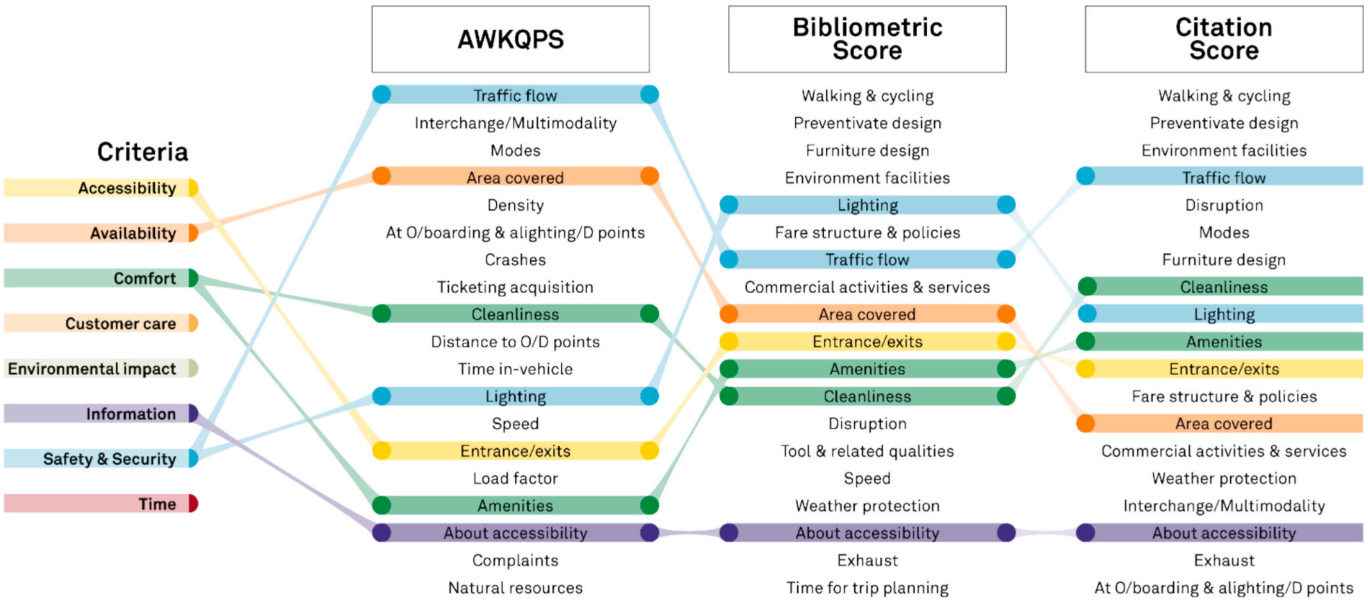

Fig. 4. Final set of KQPs ranked by AWKQPS, BS and CS. The final set of the best KQPs is given by the seven parameters that are in common among the three scores used. .
Source: personal elaboration of authors

Time are applicable across all transport systems, including walking, cycling, public transport, and shared mobility. Their universality likely explains their higher scores, as they reflect core expectations shared by all users. In contrast, criteria such as Customer Service and Information are tied to specific modes and interaction formats, and are not relevant to all systems, particularly pedestrian mobility. Environmental impact, instead, although crucial from a planning perspective due to the sector's contribution to externalities, appears less directly linked to perceived quality, highlighting a disconnect between user perceptions and the environmental implications of transport systems.

To further assess the relevance of the top-ranked KQPs, the results were compared with alternative ranking approaches to examine whether the 19 highest-ranked KQPs are regarded as equally important within the surveyed literature compiled following the PRISMA statement (Ferretto et al., 2024). The first approach relies on a Bibliometric Score (BS), defined as the number of citations received by papers employing each indicator. The second approach is based on a Citation Score (CS), which measures how frequently each parameter appears across the analysed literature, counted at most once per publication.

Although a careful comparison could not be performed since some parameters in the literature refer to a single mode of transport and a similar study has not yet been performed, BS and CS show similar results to each other but are quite different from those returned by AWKQPS based on academic expert judgments and Montecarlo’s adjustment. Compared with the AWKQPS, the strong preponderance of comfort parameters in the BS and CS is particularly noticeable. In addition, both BS and CS include parameters belonging to the criteria of Customer care and Environmental impact, which are missing in the AWKPQS. The BS shares only one Safety and Security parameter with the AWKPQS (Speed), while the CS shares three (Interchange/multimodality, Modes, At Origin/ boarding and alighting/ Destination points) corresponding to the criteria of Accessibility, Availability, and Time.

Fig. 4 shows the seven parameters that overlap in all three scores, which collectively form the final set of KQPs: About accessibility, Amenities, Cleanliness, Area covered, Entrance/exits, Lighting, and Traffic flow. The final ranking includes two parameters for Safety and Security, two for Comfort, one for Availability, one for Accessibility, and one for Information. Environmental Impact, Customer Care, and Time are excluded from the ranking. The absence of parameters for Environmental Impact and Customer Care is coherent with the initial ranking, while a parameter for Information (About accessibility), which was initially missing, appears, and Time is removed from the ranking.

This final set of quality parameters emphasises the intrinsic link between urban design and transport planning, highlighting the role of urban elements in enabling or constraining mobility. Literature consistently shows that urbanistic features such as well-designed sidewalks, barrier-free bus stops, and ramps play a crucial role in shaping accessibility and comfort (Rosa and Da Cruz Lopes, 2019; Podciborski, 2017; Douglas, 2015). The internal accessibility of transport modes, reflected in parameters like entrances and exits, is not only a matter of compliance with universal design principles (Chauhan et al., 2021) but also a determinant of seamless multimodal integration, as evidenced by the importance of dedicated access points for public transport and bike-sharing systems (Burlando et al., 2021; Shin, 2020). Availability further extends to spatial continuity and coverage, where the regularity of pedestrian and cycling infrastructure critically affects user experience and mode choice (Rossetti and Tiboni, 2020; Liang et al., 2021). Comfort is closely tied to the maintenance and cleanliness of these urban infrastructures, a factor linked to overall satisfaction (Barabino, 2018; Arellana et al., 2019; Sousa et al., 2019). Amenities such as benches, public restrooms, and drinking fountains contribute to comfort by addressing basic human needs during travel, thus enhancing the attractiveness of active and shared mobility options (Soltani et al., 2017; Groenendijk et al., 2018; Ujjwal and Bandyopadhyaya, 2021). Information, particularly related to accessibility, emerges as a key enabler for all users, but especially for those with mobility restrictions, emphasising the role of clear signage and inclusive information design in facilitating independent travel (de Aquino Traldi et al., 2022; Diana et al., 2016). Safety and security are critical factors influencing both the actual risk of crashes or crime and users’ perception of travel quality (Tan et al., 2007; Fistola et al., 2020). These dimensions affect mobility choices and comfort, underscoring the importance of designing urban environments and transport services that minimise hazards. Closely related to these aspects is the management of traffic flow, which involves balancing the interactions between pedestrians, cyclists, and motor vehicles to reduce conflicts and enhance overall safety (Rodriguez-Valencia et al., 2020; Ma et al., 2019; D’Orso and Migliore, 2019). Finally, lighting plays a fundamental role in safety, particularly in public transport stops and pedestrian paths during evening or night-time hours, contributing to a sense of security and usability in urban spaces (Jahan et al., 2020; Soltani et al., 2017; Rowangould and Corning-Padilla, 2019).

Overall, these parameters illustrate how quality in multimodal urban mobility cannot be fully understood without considering the spatial and experiential aspects of the urban environment. The interplay between infrastructure design, service provision, and user needs requires holistic planning that integrates transport with urban space to foster high-quality, sustainable mobility.

In this context, the proposed set of KQPs would be particularly relevant for emerging Mobility as a Service (MaaS) paradigm, which relies on the effective integration of multiple transport modes within a unified mobility offering. MaaS-oriented systems require high levels of accessibility, availability, information quality, comfort, and safety across all components of the travel chain to function effectively and gain user acceptance (Alyavina et al., 2022). The multidimensional nature of the identified KQPs allows them to capture both infrastructural and service-related conditions that underpin MaaS performance, supporting the evaluation of integrated mobility solutions beyond individual modes. As such, the framework can contribute to the design, monitoring, and assessment of smart mobility initiatives, where digital platforms act as enablers of multimodal integration, but the perceived quality ultimately depends on the quality of the underlying transport system.

The final set of KQPs offers a practical framework for assessing both the objective and subjective quality of multimodal urban transport systems. These parameters can support PAs and transport providers in identifying critical issues across the full travel chain, from origin to destination, encompassing infrastructure, service provision, and user experience. Unlike traditional evaluations focused on individual modes or segments, this approach enables a holistic understanding of mobility quality, guiding targeted improvements and more integrated, user-centred planning.

While the proposed KQPs ensure broad applicability across transport modes and quality dimensions, some user-centred and experience-based aspects of multimodal travel, such as reliability across chained trips, are less represented in the final selection. These dimensions may not emerge as dominant parameters when the objective is to identify stable and comparable quality parameters across multiple transport systems. However, the literature consistently shows that even in the presence of high-quality infrastructure, weaknesses in intermodal transfers, coordination between modes, or the reliability of successive trip segments can significantly undermine the overall user experience and discourage multimodal travel. Addressing these experiential and operational dimensions represents an important direction for future research, particularly through the integration of user surveys, revealed preference data, and operational performance metrics, which would allow the proposed framework to be extended towards a more behaviour-sensitive assessment of multimodal transport quality.

6. Conclusions

As the concept of sustainable mobility becomes more widespread, urban and transport planning are increasingly focused on the quality of transport and its monitoring. In this field, the focus on key quality parameters (KQPs) hinges on their capacity to deliver informative signals that highlight both strengths and weaknesses in urban transport systems. As such, selecting the appropriate KQPs is a critical factor in monitoring the quality of urban mobility systems. Previous studies have primarily focused on developing methods to select, measure, and manage the KQPs of specific transport systems, particularly public transport services. Conversely, there has been limited exploration of structured approaches for identifying and selecting the most relevant KQPs in multimodal transport systems, particularly those that ensure balanced coverage across different transport modes and quality dimensions. To address these issues, this paper contributes to the expanding literature on multimodal transport system quality in a twofold way.

First, a unified framework is introduced to systematically identify a set of KQPs through an algorithm-driven procedure, starting from an extensive pool of parameters describing the quality of different urban transport systems. This method gathers information on the relevance of quality dimensions and attributes, along with evaluations of the proposed parameters, by means of a web-based survey involving academic experts. Subsequently, the results are adjusted using Monte Carlo simulation methods to account for any coverage bias, highlighting the most promising set of KQPs. Its application improved the overall work, lending greater robustness to results that would otherwise have been based on a limited sample of responses.

Second, a comparison is made between the KQPs outcomes derived from our approach and two alternative classifications: one based on the frequency of each parameter's occurrence in scientific publications, and the other based on the ranking of bibliometric parameters. By combining these results, a focused and relevant set of seven overlapping KQPs is identified.

Beyond the identification of relevant parameters, the main advancement of the proposed framework lies in its ability to move from descriptive and exhaustive parameter lists towards a prioritised and decision-oriented set of KQPs. Unlike traditional approaches, which often provide limited guidance on how to interpret or operationalise quality parameters, the integration of AHP weighting and Monte Carlo robustness analysis allows planners to explicitly account for relative importance, uncertainty, and internal consistency. This represents a substantive step forward for multimodal planning practice, where decision-makers are increasingly required to allocate resources, design interventions, and evaluate trade-offs across multiple transport modes within complex urban environments.

The research design focused on identifying a limited set of parameters that might be applicable, without fully considering the potential trade-off between the specificity of local conditions and the generalizability or comparability of the selected parameters. Local conditions can influence the paths where these parameters are measured, thereby reflecting the uniqueness of the context. Moreover, the size and geographical distribution of the academic expert sample deserve attention. Although the survey targeted an international pool of experts identified through a systematic literature review and academic networks, the final set of respondents is geographically concentrated mainly in Europe, with a substantial share affiliated with Italian institutions. This distribution reflects the composition of the literature-based expert panel rather than an intentional regional focus of the study, but it may, nonetheless, affect the global transferability of the results. To mitigate these limitations, the methodological framework incorporated internal consistency checks through the AHP, and robustness analysis based on Monte Carlo simulation, which enhance the reliability of the findings even in the presence of a limited and unevenly distributed expert sample. Nevertheless, future research should expand the expert pool to include a wider range of geographical contexts and additional stakeholder groups (e.g., scholars and practitioners from the Global South, as well as non-academic stakeholders) to further test the applicability of the proposed KQPs and strengthen their generalisability.

In this respect, it should also be noted that the sensitivity of the resulting KQP rankings to contextual changes, such as different governance settings, urban scales, or modal compositions, was not explicitly tested in this study. While the proposed framework allows such sensitivity analyses through alternative weighting schemes, expert panel configurations, or scenario-based Monte Carlo simulations, their systematic exploration is left to future research.

This paper explored the user perspective to identify which aspects of a multimodal urban mobility system need to be measured to encourage users to adopt more sustainable transportation habits. By taking a multimodal approach, the findings offer valuable insights for all stakeholders involved in the system, including public administrations, local public transport companies, and shared mobility service providers, who can collaborate to create a high-quality transportation supply. In this regard, a possible development of this research could include judgments not only from academic experts, but also from municipal technicians, freelancers in the transport sector, public transport companies, or companies that provide sharing services. It should also be noted that, as the KQPs were derived exclusively from academic expert judgments, their alignment with actual user priorities, operational constraints, and real-world travel behaviour remains to be empirically validated. Incorporating input from transport users, municipal technicians, public transport operators, and mobility shared service providers in future studies would ensure that the selected KQPs accurately reflect on-ground multimodal mobility conditions.

Applying the methodology to real operational urban transport systems will be a natural development in future work, providing opportunities to validate the KQPs, refine the framework, and assess its practical relevance in different multimodal urban contexts. Although no specific multimodal urban transport system was empirically analysed in this study, the methodology is fully designed to be implemented in practical contexts. Its structured approach, combined with expert-based weighting and robustness analysis, allows for consistent evaluation and selection of KQPs in diverse urban transport systems, providing a framework that can be applied and tested in future studies.

From a practical perspective, the proposed KQP framework can support public authorities, planners, and transport service providers in structuring comprehensive and manageable quality assessments. By identifying a limited set of weighted and validated parameters applicable to all modes of transport, the framework facilitates a clearer definition of investment priorities, design interventions, and operational improvements in multimodal corridors. Each KQP captures a specific dimension of urban mobility quality, such as accessibility, safety, comfort, or spatial coverage, enabling decision-makers to identify critical areas for intervention, assess trade-offs among different modes, and monitor quality over time. In this sense, the methodology enhances transparency in resource allocation, supports evidence-based decision-making, and is particularly well-suited to contemporary planning contexts characterized by integrated mobility strategies, limited resources, and a growing demand for responsible, user-centered transport policies.

Finally, this study focuses on assessing the quality of a multimodal and sustainable urban transport system, and as such, it excludes transport systems in suburban areas (e.g., rail systems) and less-sustainable modes of transport (e.g., private cars). However, the study could be expanded to include additional transport systems, broadening the scope of this research.

Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve English language and readability. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

Review board statement

This study was reviewed and approved by the CeSCAM ethics advisory council (approval n. 024–0001, 09 May 2024). Moreover, all participants gave their informed consent for inclusion before they participated in the study.

CRediT authorship contribution statement

Laura Ferretto: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Martina Carra:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Benedetto Barabino:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

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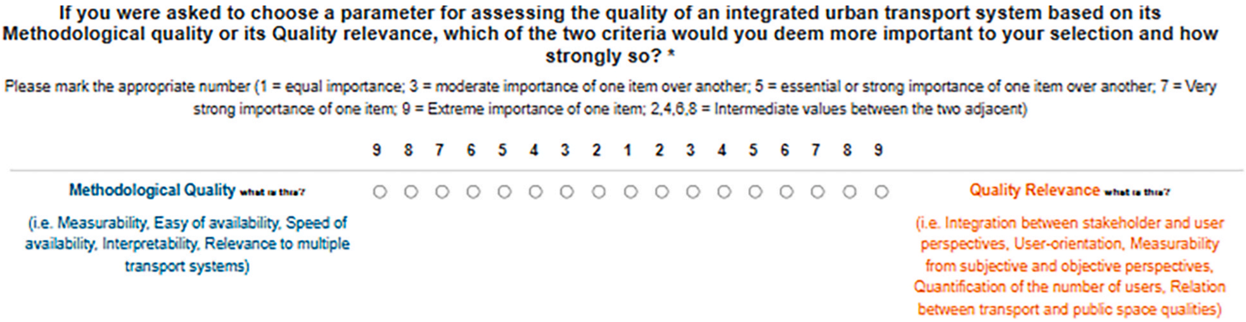
Appendix A

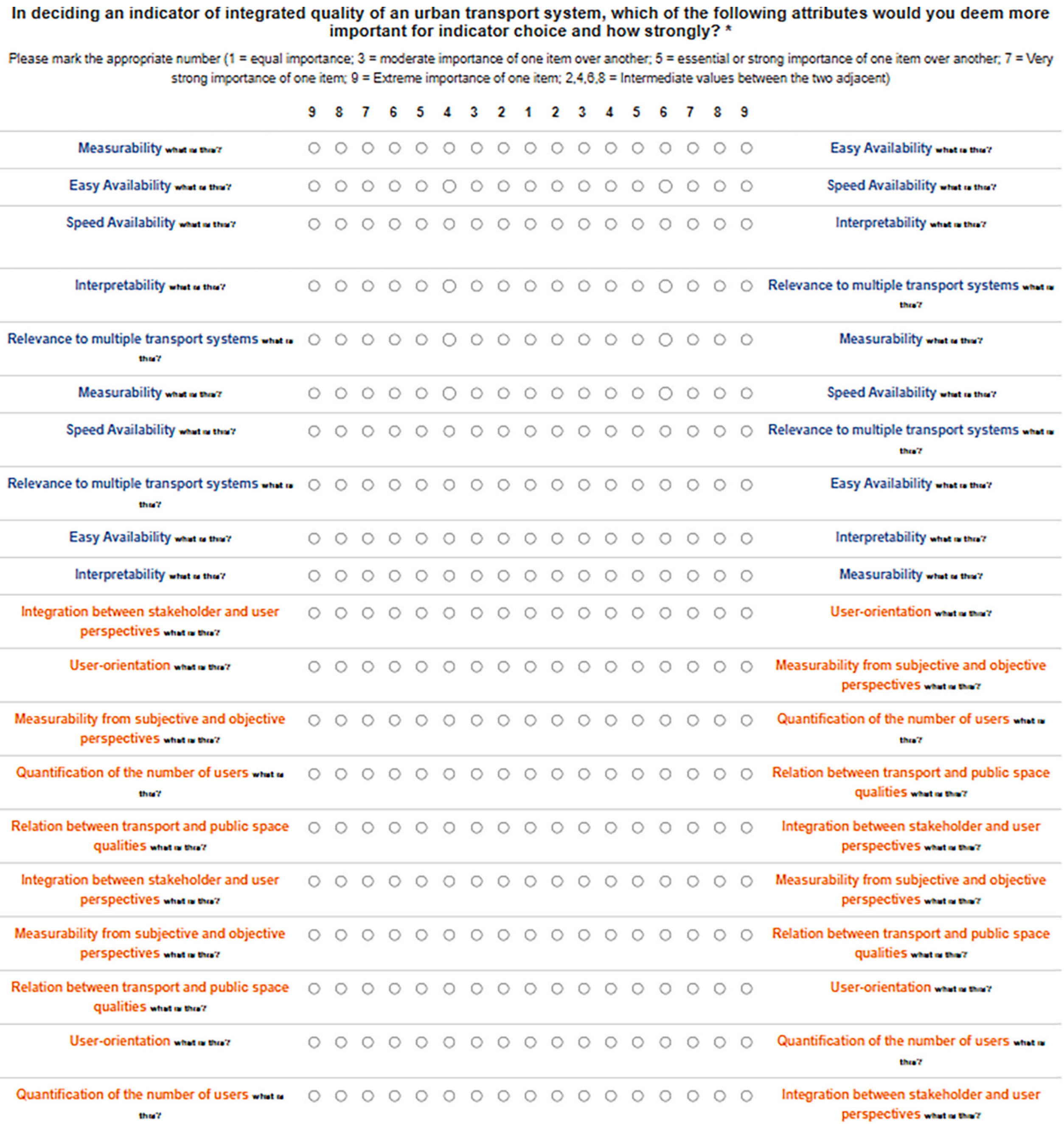


If you were asked to choose a parameter for assessing the quality of an integrated urban transport system based on its Methodological quality or its Quality relevance, which of the two criteria would you deem more important to your selection and how strongly so? *

Please mark the appropriate number (1 = equal importance; 3 = moderate importance of one item over another; 5 = essential or strong importance of one item over another; 7 = Very strong importance of one item; 9 = Extreme importance of one item; 2,4,6,8 = Intermediate values between the two adjacent)

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Methodological Quality what is this? (i.e. Measurability, Easy of availability, Speed of availability, Interpretability, Relevance to multiple transport systems)	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Quality Relevance what is this? (i.e. Integration between stakeholder and user perspectives, User-orientation, Measurability from subjective and objective perspectives, Quantification of the number of users, Relation between transport and public space qualities)

Fig. A1. Excerpt from the structured web survey comparing the two components

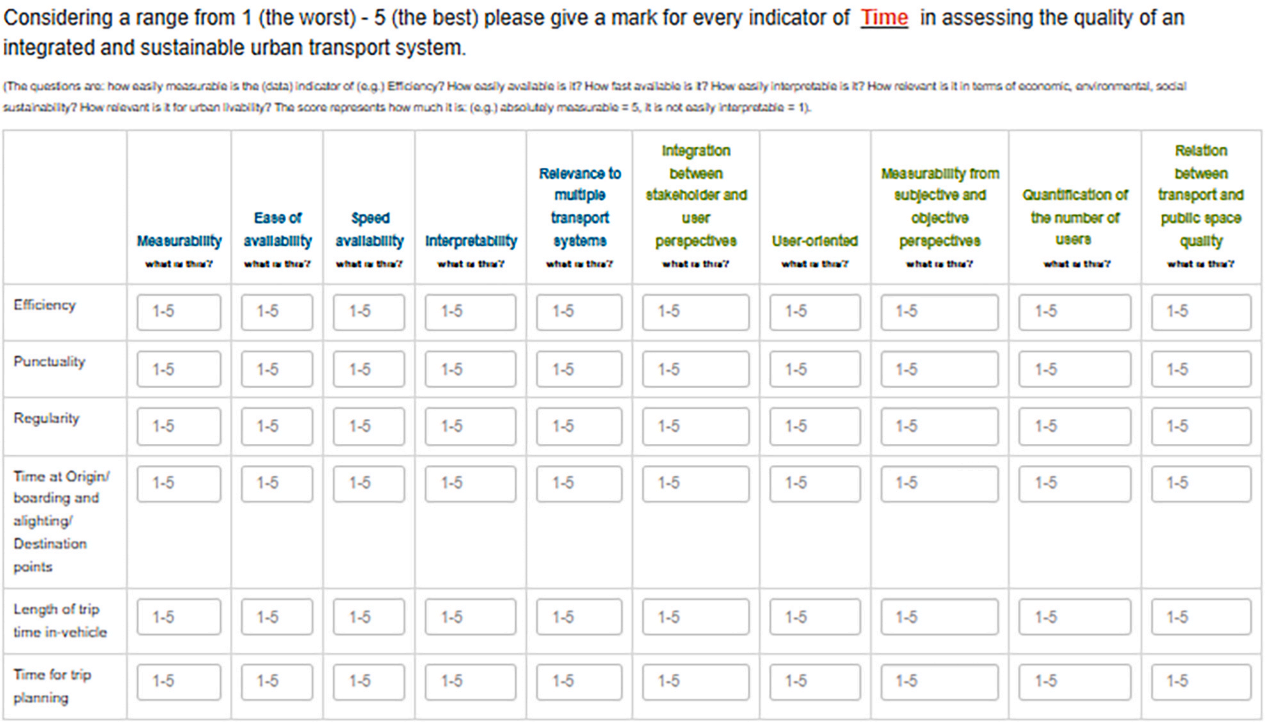


In deciding an indicator of integrated quality of an urban transport system, which of the following attributes would you deem more important for indicator choice and how strongly? *

Please mark the appropriate number (1 = equal importance; 3 = moderate importance of one item over another; 5 = essential or strong importance of one item over another; 7 = Very strong importance of one item; 9 = Extreme importance of one item; 2,4,6,8 = Intermediate values between the two adjacent)

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Measurability what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Easy Availability what is this?
Easy Availability what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Speed Availability what is this?
Speed Availability what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Interpretability what is this?
Interpretability what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Relevance to multiple transport systems what is this?
Relevance to multiple transport systems what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Measurability what is this?
Measurability what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Speed Availability what is this?
Speed Availability what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Relevance to multiple transport systems what is this?
Relevance to multiple transport systems what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Easy Availability what is this?
Easy Availability what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Interpretability what is this?
Interpretability what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Measurability what is this?
Integration between stakeholder and user perspectives what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	User-orientation what is this?
User-orientation what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Measurability from subjective and objective perspectives what is this?
Measurability from subjective and objective perspectives what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Quantification of the number of users what is this?
Quantification of the number of users what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Relation between transport and public space qualities what is this?
Relation between transport and public space qualities what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Integration between stakeholder and user perspectives what is this?
Integration between stakeholder and user perspectives what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Measurability from subjective and objective perspectives what is this?
Measurability from subjective and objective perspectives what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Relation between transport and public space qualities what is this?
Relation between transport and public space qualities what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	User-orientation what is this?
User-orientation what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Quantification of the number of users what is this?
Quantification of the number of users what is this?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Integration between stakeholder and user perspectives what is this?

Fig. A2. Excerpt from the structured web survey comparing the ten attributes.



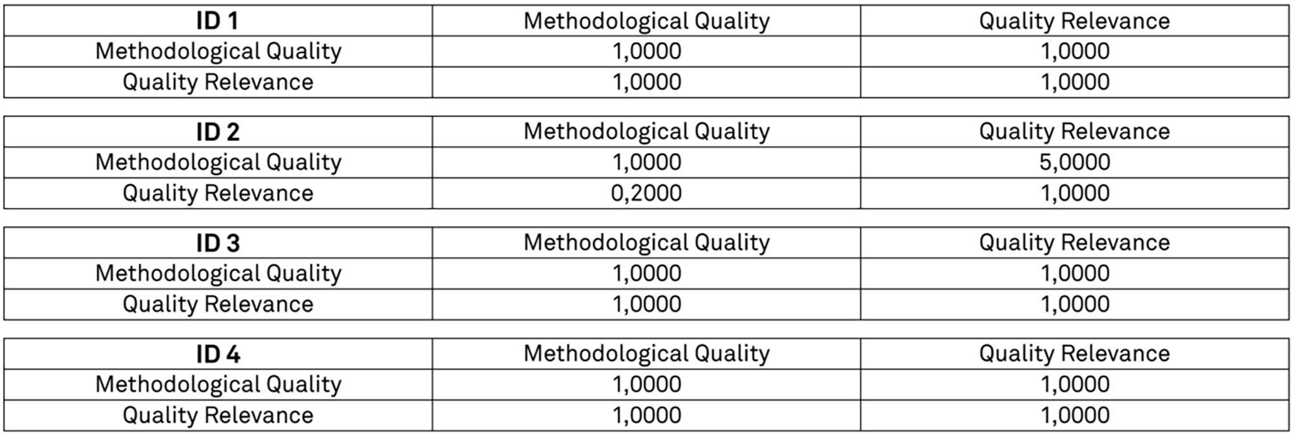
Considering a range from 1 (the worst) - 5 (the best) please give a mark for every indicator of Time in assessing the quality of an integrated and sustainable urban transport system.

(The questions are: how easily measurable is the (data) indicator of (e.g.) Efficiency? How easily available is it? How fast available is it? How easily interpretable is it? How relevant is it in terms of economic, environmental, social sustainability? How relevant is it for urban livability? The score represents how much it is: (e.g.) absolutely measurable = 5, it is not easily interpretable = 1).

	Measurability what is this?	Ease of availability what is this?	Speed availability what is this?	Interpretability what is this?	Relevance to multiple transport systems what is this?	Integration between stakeholder and user perspectives what is this?	User-oriented what is this?	Measurability from subjective and objective perspectives what is this?	Quantification of the number of users what is this?	Relation between transport and public space quality what is this?
Efficiency	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5
Punctuality	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5
Regularity	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5
Time at Origin/ boarding and alighting/ Destination points	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5
Length of trip time in-vehicle	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5
Time for trip planning	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5	1-5

Fig. A3. Excerpt from the structured web survey comparing the 65 quality parameters with attributes. In particular, this figure shows the structure for evaluating the criterion of Time.

Appendix B



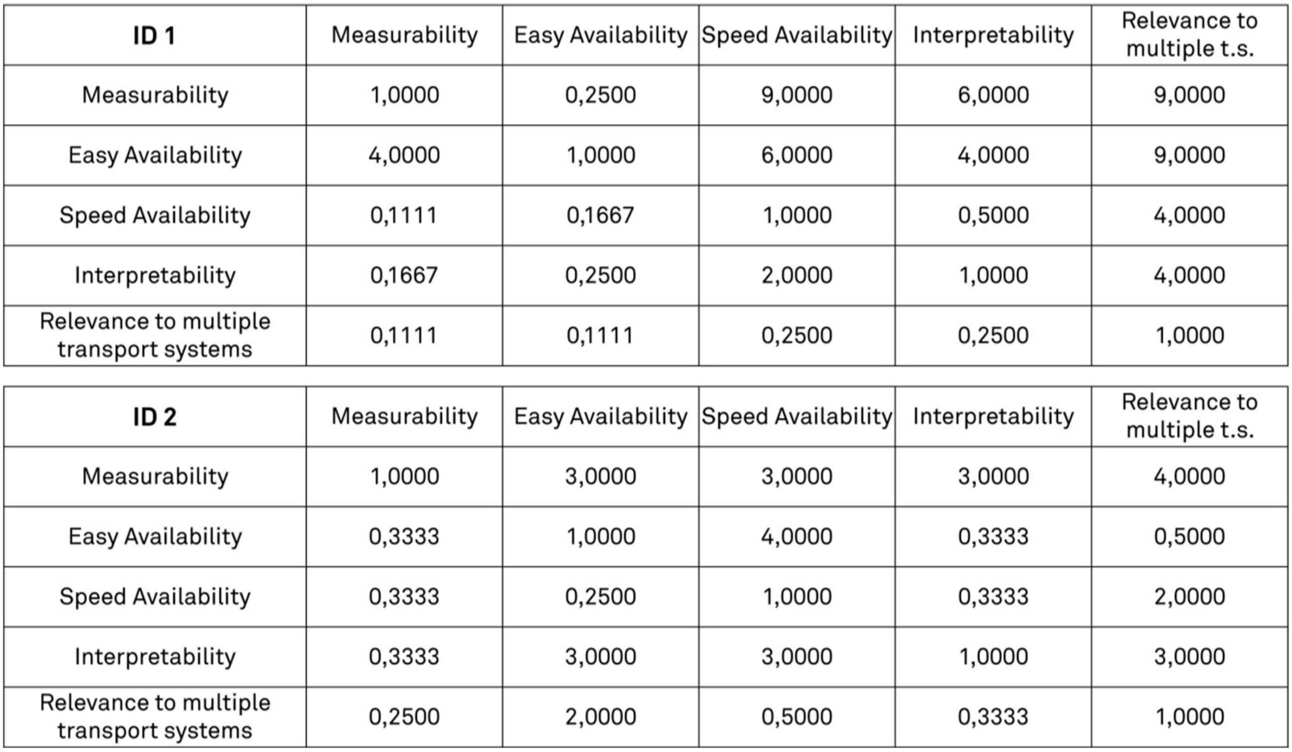
ID 1	Methodological Quality	Quality Relevance
Methodological Quality	1,0000	1,0000
Quality Relevance	1,0000	1,0000

ID 2	Methodological Quality	Quality Relevance
Methodological Quality	1,0000	5,0000
Quality Relevance	0,2000	1,0000

ID 3	Methodological Quality	Quality Relevance
Methodological Quality	1,0000	1,0000
Quality Relevance	1,0000	1,0000

ID 4	Methodological Quality	Quality Relevance
Methodological Quality	1,0000	1,0000
Quality Relevance	1,0000	1,0000

Fig. B1. Excerpt from the Excel matrix structured to disaggregate the academic experts' ratings, where each ID number corresponds to one academic expert. In the original file, this comparison of the two components includes 27 matrices corresponding to the 27 academic experts' respondents.



ID 1	Measurability	Easy Availability	Speed Availability	Interpretability	Relevance to multiple t.s.
Measurability	1,0000	0,2500	9,0000	6,0000	9,0000
Easy Availability	4,0000	1,0000	6,0000	4,0000	9,0000
Speed Availability	0,1111	0,1667	1,0000	0,5000	4,0000
Interpretability	0,1667	0,2500	2,0000	1,0000	4,0000
Relevance to multiple transport systems	0,1111	0,1111	0,2500	0,2500	1,0000

ID 2	Measurability	Easy Availability	Speed Availability	Interpretability	Relevance to multiple t.s.
Measurability	1,0000	3,0000	3,0000	3,0000	4,0000
Easy Availability	0,3333	1,0000	4,0000	0,3333	0,5000
Speed Availability	0,3333	0,2500	1,0000	0,3333	2,0000
Interpretability	0,3333	3,0000	3,0000	1,0000	3,0000
Relevance to multiple transport systems	0,2500	2,0000	0,5000	0,3333	1,0000

Fig. B2. Excerpt from the Excel matrix structured to disaggregate the academic experts' ratings, where each ID number corresponds to one academic expert. In the original file, this comparison of the two components includes 24 matrices corresponding to the 27 academic experts' respondents minus the three evaluations excluded because they lacked credibility.

Appendix C

Table C1
Final ranking of Weighted Key Parameters Quality Scores.

n	Criteria	Parameter I	Parameter II	WKPQS	AWKPQS	Scores variation
1	Comfort	Seating and personal space for public transport vehicles	At b/a points*	4.297	4.302	=
2	Availability	Operation	Frequency*	4.197	4.227	–
3	Safety & Security	Freedom from accident	Traffic flow	4.233	4.221	+
4	Accessibility	External interface	Interchange / multimodality	4.128	4.157	+
5	Comfort	Seating and personal space for public transport vehicles	In vehicle*	4.150	4.147	+
6	Availability	Operation	Operating hours*	4.031	4.075	–
7	Availability	Network	Modes	4.143	4.069	–
8	Availability	Network	Area covered	4.058	4.038	–
9	Comfort	Ambient conditions	Density	3.909	3.981	–
10	Time	Adherence to schedule / Reliability	Punctuality*	4.022	3.934	+
11	Time	Length of trip time	At Origin/boarding and alighting/Destination points	3.913	3.915	–
12	Safety & Security	Freedom from accident	Crashes	3.908	3.908	=
13	Accessibility	Ticketing availability	Ticketing acquisition	3.847	3.853	=
14	Comfort	Ambient conditions	Cleanliness	3.832	3.834	=
15	Availability	Network	Distance to O/D points	3.746	3.793	+
16	Time	Length of trip time	Time in-vehicle	3.796	3.781	=
17	Safety & Security	Freedom from crime	Lighting	3.809	3.700	+
18	Safety & Security	Freedom from accident	Speed	3.708	3.768	+
19	Accessibility	Internal interface	Entrance/exits	3.748	3.750	–
20	Accessibility	Ticketing availability	Ticketing validation*	3.769	3.732	+
21	Availability	Operation	Load factor	3.745	3.718	–
22	Information	General information	About time*	3.746	3.715	=
24	Comfort	Complementary facilities	Amenities	3.777	3.715	–
23	Comfort	Complementary facilities	Commercial activities and services	3.775	3.715	+
25	Comfort	Ergonomics	Ease of movement*	3.668	3.699	–
26	Comfort	Path comfort	Walking and cycling	3.702	3.697	=

(continued on next page)

Table C1 (*continued*)

n	Criteria	Parameter I	Parameter II	WKPQS	AWKPQS	Scores variation
27	Information	General information	About accessibility**	3.709	3.684	–
28	Customer care	Customer interface	Complaints**	3.587	3.655	–
29	Information	General information	About availability	3.598	3.635	–
30	Comfort	Complementary facilities	Environment facilities	3.658	3.624	+
31	Comfort	Ambient conditions	Disruption	3.617	3.623	–
32	Customer care	Ticketing options	Fare structure and policy	3.650	3.621	+
33	Safety & Security	Freedom from accident	Presence/visibility of supports, e.g. handrails	3.574	3.606	=
34	Time	Adherence to schedule / Reliability	Regularity*	3.529	3.572	=
35	Information	General information	About security	3.515	3.488	=
36	Comfort	Ambient conditions	Weather protection	3.494	3.474	=
37	Comfort	Ambient conditions	Noise	3.449	3.449	=
38	Information	General information	About comfort	3.441	3.421	=
39	Comfort	Complementary facilities	Entertainment*	3.389	3.402	–
40	Customer care	Ticketing options	Consistent price calculations	3.408	3.389	+
41	Accessibility	Internal interface	Internal movement	3.359	3.326	=
42	Comfort	Ride comfort	Driving*	3.346	3.296	=
43	Safety & Security	Freedom from crime	Public safety monitoring	3.279	3.295	–
44	Information	General information	About customer care	3.223	3.280	–
45	Comfort	Ergonomics	Furniture design	3.308	3.265	+
46	Time	Length of trip time	Time for trip planning	3.300	3.259	+
47	Safety & Security	Freedom from crime	People (mis)behaviour	3.221	3.250	=
48	Information	General information	About source of information	3.216	3.238	=
49	Customer care	Assistance	Customer orientation	3.154	3.183	=
50	Time	Adherence to schedule / Reliability	Efficiency*	3.112	3.103	=
51	Comfort	Ambient conditions	Odour	3.043	3.058	+
52	Safety & Security	Emergency management	Facilities and plans	2.991	3.020	–
53	Safety & Security	Freedom from accident	Preventive design	2.964	3.018	–
54	Safety & Security	Freedom from accident	Avoidance/visibility of hazards	2.974	3.001	–
55	Information	General information	About environmental impact	3.058	2.997	+
56	Comfort	Ambient conditions	Visual pollution	3.002	2.992	+
57	Safety & Security	Freedom from accident	Travel behaviour*	3.022	2.955	+
58	Customer care	Customer interface	Tools and related qualities	2.982	2.899	–
59	Customer care	Staff	Staff availability*	2.883	2.888	=
60	Customer care	Commitment	Innovation and initiative	2.880	2.852	=
61	Customer care	Staff	Staff skills (behaviour)	2.817	2.822	
62	Comfort	Ambient conditions	Atmosphere	2.820	2.799	–
63	Environmental impact	Pollution and health	Natural resources**	2.743	2.796	–
64	Environmental impact	Pollution and health	Exhaust	2.763	2.709	+
65	Customer care	Staff	Staff appearance*	2.582	2.644	=

* Those highlighted in yellow are the parameters that do not evaluate at least 3/4 modes of transport included in this research, which, therefore, are excluded from the ranking.

** Those highlighted in green are the parameters that belong to the criteria excluded from the first quartile, which, therefore, were added to the final ranking.

Data availability

The data that has been used is confidential.

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