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Assessing Tram-Train feasibility via multicriteria approach: The case of Brescia (Italy)

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A R T I C L E I N F O

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A B S T R A C T

Tram-Trains (TTs) are advanced, sustainable mobility systems that merge the best features of trams with regional railways. However, integrating heavy rail and tram operations introduces complexity in various areas, including infrastructure (track design, vehicles, power supply, and facilities) and organisational management. Ensuring compatibility often requires compromise solutions, such as adjusting the track gauges, modifying vehicle specifications, integrating power supply systems, and coordinating scheduling and operational procedures. Additionally, although this system is familiar to the transport community, there is a notable lack of studies utilising relevant planning tools and evaluation frameworks to assess the system's applicability and analyse potential alternatives, thereby enabling the selection of the best option for implementation in the target context.

The framework applied in this paper aims to address this gap in the existing literature. It employs a combined multi-criteria analysis approach: Analytic Hierarchy Process (AHP) to establish a hierarchy of evaluation criteria and *ELimination Et Choix Traduisant la REalité* (ELECTRE) to determine the best compromise alternative. Moreover, the framework benefits from the input of practitioners and academics who were involved to assign importance to evaluation criteria and Monte Carlo simulation methods to include uncertainty. This framework enables the analysis of various design options and identifies the most suitable one for implementing a TT system in the studied context, precisely the territory of Brescia (Italy). Therefore, this study shows the potential viability of an interoperable system, such as the TT, which could be applicable in the selected area. These results are helpful since they might guide city planners and practitioners and serve as a benchmark for the scientific community while evaluating the applicability of the system.

1. Introduction

A tram-train (TT) is an interoperable type of rail transit that operates by meeting the standards of both the light rail system and mainline standards permitting operation alongside trains. This allows services that utilise existing urban light rail systems, railway networks, and related stations. Therefore, it aims to maximise the benefits of both tram and train systems. This is accomplished by enabling TT vehicles to utilise tracks alongside trams and heavy trains, thereby eliminating the necessity for passengers to switch between different modes of transportation. According to AVG (2017), the idea of linking tram and railway lines with one another was employed in Karlsruhe and realised gradually in the 1980s and 1990s. This idea, known as the Karlsruhe model or TT, has been adopted by other European cities since then (Naegeli et al., 2012). Previous experiences showed how introducing TT systems, particularly the lighter ones, can alleviate line capacity limitations and enhance travel times. This advancement has the potential to improve overall transportation, streamline commuting, reduce reliance on personal vehicles, and enable efficient and convenient transportation for passengers. Therefore, it can promote more sustainable transport habits and be a strategic option to discourage the culture of using private cars.

However, by introducing large TT systems projects, the operation of light rail vehicles on conventional railway infrastructure requires addressing numerous issues (Novales et al., 2002a). These are linked to the context of infrastructures, technical complications, economic viability, and so on. The related literature highlighted that the focus has primarily been on in-depth studies on the experimentation of new vehicle components, design aspects tied to infrastructure, and the feasibility of technical-economic aspects.

As for transportation planning, feasibility assessment aspects are crucial, considering existing infrastructure and potential additions (e.g.,

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Potěšil and Molková, 2006). The existing literature primarily focused on descriptive technical feasibility or on defining standardised frameworks (Novales et al., 2003; Maternini et al., 2014a; Maternini et al., 2014b; Camacho and Martin, 2015; Merkushev et al., 2019; Corazza and Favaretto, 2019). Recently, there has been a concentration of studies on numerical assessment methods, mainly focused on Cost-Benefit Analysis (CBA) with several degrees of depth (De Aloe et al., 2023; Hickman and Dean, 2018; Ventura et al., 2022). However, CBAs may be limited in scope due to their exclusive focus on monetary criteria, considering the vastness and complexity of these systems. To tackle this issue, there is a need for methodologies that facilitate a comprehensive assessment, incorporating accurate studies that can effectively align economic, social, financial, environmental, and logistical sustainability (Cappelli and Nocera, 2006). An example of such methodology is Multi-Criteria Decision-Making (MCDM), as demonstrated in several transportation planning topics: e.g., the evaluation of dangerous road sections (e.g., Nenadić, 2019), road maintenance prioritisation (e.g., Sayadinia and Beheshtinia, 2021), selection of alternative fuels for bus fleets (Borghetti et al., 2024; Ozdagoglu et al., 2022). The MCDMs were applied partially in the feasibility assessment of a TT system (Ventura et al., 2022) or in a qualitative way (L'Hostis et al., 2017).

Consequently, the analysis of the existing literature revealed a gap: the need for studies utilising planning tools and MCDM assessment frameworks to ascertain the feasibility of implementing a TT system. Therefore, this case study employs the goals above involving a dual-faceted data analysis conducted using the MCDM techniques. It combines two methods: the Analytical Hierarchy Process (AHP) and the *ELimination Et Choix Traduisant la REalité* (ELECTRE). As Saaty (1987) explained, the AHP aims to gauge the relative significance of criteria, comprehending the extent to which one element holds more importance than another in terms of the overarching objective. On the other hand, the ELECTRE method focuses on finding a good compromise solution among different TT routes by accounting for the relative importance of criteria and considering the previously established hierarchy, as elucidated by Figueira et al. (2016). Additionally, the entire method is enhanced by the contributions of both practitioners and academics, who participated in assigning importance to evaluation criteria and Monte Carlo simulation methods to account for uncertainty.

In summary, this research offers a twofold contribution to the current knowledge. Theoretically, it introduces novel perspectives on the viability of a TT system, offering an illustrative instance of its practical application in the Italian context and establishing a foundation for forthcoming inquiries. What distinguishes this study from earlier research is its incorporation of a comprehensive and multi-faceted array of criteria weighted by involving academics and practitioners, extending beyond financial and cost-related elements to encompass sustainability with social, environmental and road safety aspects. Moreover, it considers the replication of approaches in geographical and operational contexts.

The remainder of the study is as follows. Section 2 examines the current state of the art on TT systems and the primary research gaps. Section 3 presents the framework for TT system evaluation. Section 4 applies the framework in the case study of Brescia (Italy) and discusses the key findings. Finally, Section 5 draws conclusions, including research limitations and future perspectives.

2. State of the art

While TT systems offer various advantages, there are challenges associated with implementing them. However, research on TT systems is surprisingly limited, as far as the authors know, and few studies are available. The literature review tried to oversee the studies available on hand by grouping them into three main categories. They are concerned with (1) the characteristics of TT systems, (2) vehicle components and technical compatibility, and (3) feasibility assessment methods and case studies.

The first category of studies defined the characteristics of TT systems in regional and urban areas, i.e., from railway tracks to tram ones (AGV, 2017). The duality characteristics of the system have led to defining the required solutions to numerous technical issues: traction power supply system, rolling stock design, gauge compatibility, wheel and rail profile, structural strength, passenger access, context suitability criteria for implementation (Naegeli et al., 2012), regulatory issues (Durzynski et al., 2018). For instance, Novales et al. (2002b) emphasised the issues of vehicle functional compatibility on the shared track, adaptations required (e.g., pantograph, coupling for breakdowns, signalling), and tracking and control systems to maintain safety when incorporating light vehicles onto the shared track.

The second category of studies presented some technical issues of TT vehicle components. For instance, Novales et al. (2007) proposed a methodology based on genetic algorithms to enhance wheel profiles by considering certain physical phenomena that occur when vehicles run on tracks. Based on the application in a Spanish case study, the results showed significant improvements in wheel profile performance. Bruner and Rizzetto (2008) compared the dynamic behaviour of a TT vehicle equipped with both wheels with a Tangential-Tread profile and standard wheels in the railway context. Results showed an increase in rail wear compared to traditional profiles and a potential modification of the bogies' dynamic behaviour. Consequently, other studies proposed different technical solutions. Bocz and Vinkó (2016) proposed new profile geometries for safe vehicle operation and reduced wheel-rail contact wear. Crosbee et al. (2017) developed a new wheel profile for TT vehicles, optimised for operation on both tram and train tracks. Both studies developed the new profiles using vehicle dynamic simulations and custom software. Finally, Jeong et al. (2017) introduced models to evaluate vehicle performance through virtual simulation, identifying the best passenger comfort index and minimum derailment coefficient.

The third category of studies examined the feasibility of implementing TT systems, and scholars tackled this subject from diverse corners. The assessment considered three different economic approaches: descriptive, cost-benefit and multicriteria. The descriptive approach comprehended studies such as Maternini et al. (2014a) and Camacho and Martin (2015). The former proposed a possible TT application in compliance with the new national (Italian) guidelines issued in 2013. Moreover, the authors analysed different kinds of TT systems and realisation/operation costs, highlighting the most relevant technical issues deriving from their application to the Brescia context. The latter developed a framework to standardise the essential prerequisites for the secure and economically viable introduction of TT systems. The second approach of Cost-Benefit Analysis is the most developed according to different degrees of depth. Hickman and Dean (2018) presented a synthesised assessment to emphasise some critical issues of the approach itself. Ventura et al. (2022) put forth an in-depth dual-blocked framework to evaluate the applicability of a TT in South Italy. In the former block, a contextual assessment gauges a city's suitability for a TT system, employing an AHP coupled with a weighted global score. The latter block involves a cost-benefit analysis aimed at appraising the economic viability of the project, contingent upon the city receiving a favourable evaluation for implementation. De Aloe et al. (2023) conducted a comprehensive study involving economic evaluations of implementing a TT system within the mid-sized city of Brescia. Their findings detailed costs and benefit estimates and revealed the potential feasibility of such a transportation system within the specific case study. Finally, the third approach concerned MCDM approaches of type Multi-Attribute Decision Making. For instance, L'Hostis et al. (2017) utilised a qualitative MCDM to select a new public transport system linked to urban development. Similarly, Corazza and Favaretto (2019) employed the MCDM in a multi-faceted manner to evaluate the transformation of seven bus stops into TT stops, considering various transportation and urban factors. Recently, Boray et al. (2024) have conducted a feasibility study of a TT service powered by zero-emission hydrogen fuel cell/battery hybrid rail power technology along a 342 km route of the Canadian rail hub. They showed that five tons of hydrogen per day would be consumed over 16 h daily by the fleet of 16 TT vehicles. The results offer important insights into technical aspects and energy requirements in developing zero-emission passenger TT services.

In summary, by examining the current state of the art, it was possible to identify and classify the unique features of TT systems. Furthermore, the challenges associated with implementing such systems in urban environments and the corresponding studies to mitigate these issues were outlined. The literature provided a comprehensive overview of this sustainable mode of transportation. However, there is a notable absence of studies that provide feasibility assessment methods. Specifically, it is noteworthy that in most studies, the MCDM has been used to inform other studies rather than being employed to elucidate the selection of the most suitable TT routes among alternatives. A discernible pattern emerges from these earlier works that utilised MCDM techniques, indicating a relatively narrow focus on specific aspects of TT alternatives. Moreover, the assessment of factors was qualitative (e.g., high, average, weak) and addressed to define the potentials and impacts of implementing a TT system. This emphasises the uniqueness of the current study, which aims to apply MCDM more comprehensively, seeking to analyse and select the most suitable alternatives from the proposed TT options.

3. Methodological framework

The framework serves as a decision-making tool for city planners and transportation professionals, providing a baseline for the scientific community when assessing the applicability of the TT system. It consists of three main phases with seven related steps. Phase I encompasses the delineation of diverse options, notably the accessible tram and train routes (alternatives), alongside the identification of the criteria employed to make selections. In Phase II, stakeholders are engaged to gather their opinions regarding each criterion. Lastly, Phase III employs the AHP and ELECTRE methods to find the best compromise solution, ultimately leading to the ranking of the options. Fig. 1 illustrates the phases and steps, described in detail in the following sections.

3.1. Alternatives and judgment criteria phase (I)

Phase I entails preliminary activities aimed at delineating various types of TT routes (i.e., alternatives) that may be pertinent, as well as the criteria for their assessment according to Step 1) and Step 2), respectively, before applying the multicriteria decision methods. The primary objective of Step 1) is to define the finite number of alternatives that will be considered for comparison among the available TT routes. Step 2) focuses on assessing each alternative against each criterion. Note that each multicriteria decision problem could involve a multitude of 'criteria' representing various perspectives from which each alternative can be evaluated and, consequently, assessed. Typically, these criteria are in conflict, as enhancing performance in one criterion may result in a detriment to another. Hence, Step 2) aims to structure the problem hierarchically: after defining the objective, the issue should be broken down into criteria and, where applicable, sub-criteria and further sub-sub-criteria, selected based on the research objective. Noteworthy, while all criteria are universal, each may carry a unique level of importance, as it may vary to reflect different viewpoints.

A checklist for successful TT systems can be referenced during the evaluation of routes and the establishment of criteria for alternative routes, as outlined by Naegeli et al. (2012). This study systematically considered criteria associated with effective TT systems, concurrently addressing economic, environmental, social, and safety considerations alongside the provided checklists. Therefore, it develops a comprehensive understanding of the external (or contextual) and inherent factors influencing the successful implementation of a TT transportation system. Therefore, the analysis aims to ensure the seamless integration of the system, thereby maximising benefits, minimising adverse effects, and enhancing the overall transportation infrastructure and services.

3.2. Interactive phase (II)

Phase II involves identifying a group of stakeholders and gathering their opinions on criteria and sub-criteria. This phase runs according to Step 3) and 4) of the process. These criteria, collectively referred to as "criteria" unless specified otherwise, are crucial factors to be evaluated. However, determining their importance is a complex task and requires specialised knowledge. Hence, Step 3) involves experts, such as academicians, managers of public transport systems, and policymakers, who can provide valuable insights based on their daily operational judgment from their respective perspectives. Involving experts is highly recommended because their diverse viewpoints can lead to various evaluations of the criteria. However, these opinions may differ since the specific knowledge of the experts involved varies from group to group and from person to person. Therefore, several authors have implemented different methods for weighting the "items", namely, e.g., criteria, features, and factors (e.g., Hens and De Wit, 2003; Wang and Lee, 2009). Nonetheless, since the MCDM method is applied in this study, it is also used in the weighing process. This study applies the AHP among the different methods due to its positive mitigation of bias risks (Saaty, 1987, 1994). This relevant weighting is also essential for the subsequent application

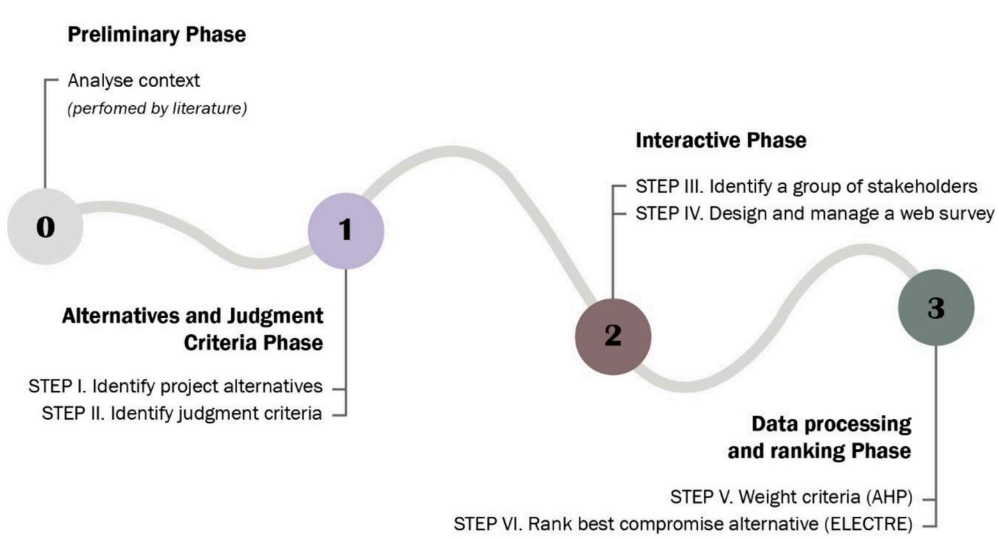

Fig. 1. Conceptual model of the methodological framework.

of MCDM methods, which will be discussed in the next phase.

While experts can be involved in various ways, this study opted for a survey method, enabling the participation of the maximum number of relevant experts, as outlined in Step 4). A web survey was selected as the most appropriate survey method for involving interested experts. The selection was driven by its advantages, quick access to experts, cost-effectiveness, direct online data collection, and the ability to process received data without additional manipulation. While a traditional email survey could have been an option, the benefits of the web survey outweighed the former, making it the preferred choice for this study.

3.3. Data processing and ranking phase (III)

Phase III processes data collected among the experts and computes weighting by applying AHP in Step 5). Finally, the ELECTRE method computed in Step 6) (possibly) determines the best-compromised alternative. The method partially draws inspiration from earlier studies with different focuses and methodological developments (e.g., Borghetti et al., 2024; Carra et al., 2023).

More formally, let A be the set of alternatives and $a \in A$ and $b \in A$ be two specific alternatives; I be the set of criteria and $i \in I$ and $j \in I$ be two specific criteria; E be the set of experts and $e \in E$ be a specific expert; W be the set of weights and $w \in W$ be a specific weight; P be the set of performance measures and $p_{ai} \in P$ a specific performance measure associated with $a \in A$ and $i \in I$; X be the set of utility measures and $x_{ai} \in X$ be a specific utility associated with $a \in A$ and $i \in I$.

Step 5) and Step 6) are presented in what follows, considering the previous notation.

3.3.1. Step 5: AHP

The survey method is structured to process data with the AHP. Therefore, the judgments of experts consider pairwise comparisons among criteria, and the choices refer to a ratio scale. The scale is applied to each set of pairwise comparisons to assess the coherence or divergence of the provided judgments, i.e., to counteract potential biases within the decision-making process. Notably, the AHP exhibits the ability to address conflicts or discrepancies among groups with differing and possibly conflicting objectives or viewpoints. Moreover, the results yielded by the AHP can be of relevant value due to their consideration of multiple aspects and diverse measurements that characterised the criteria for evaluating alternatives.

More specifically, a matrix of pairwise comparisons between criteria is constructed for each expert $e \in E$ engaged. The rows ($i \in I$) and columns ($j \in I$) of this matrix represent individual criteria. Each entry (denoted as a_{ij}) contains the ratio of the weights assigned to one criterion (i.e., $i \in I$) against another (i.e., $j \in I$), i.e., $a_{ij} = \frac{w_i}{w_j}$. Next, an overall weight vector W_i is computed for each criterion as illustrated in Eq. (1) and, next, normalised through the average arithmetic method (among the several available approaches).

$$W_i = \sqrt[I]{\prod_{j \in I} a_{ij}}; \quad \forall i \in I \tag{1}$$

However, this process can highlight inconsistent judgments. Consequently, a consistency test must be performed to validate the dependability of assessments originating from each matrix. It is checkable by the Consistency Ratio (CR; Eq. (2)), which relates the choices reported in the survey to the maximum eigenvalue and the Random consistency Index (RI). The RI is a tabled function depending on the number of criteria considered (Saaty, 1980, p.21).

$$CR = \frac{\frac{\sum_{i \in I} \left[\frac{\sum_{j \in I} (a_{ij} * W_j)}{W_i} \right]}{|I|} - |I|}{RI \bullet (|I| - 1)}; \tag{2}$$

Pairwise comparisons are deemed reliable if the CR <0.1 (10%) or if the judgments of experts are coherent and align with the preferences expressed in the survey. If CR exceeds this threshold, experts would again be engaged to reevaluate their assessments since their judgments would be inconsistent. Additional insights into the implementation of AHP can be found in Saaty's works (Saaty, 1987, 1994). Notably, distinct matrices are constructed for criteria, sub-criteria, and sub-sub-criteria corresponding to each expert $e \in E$. Furthermore, experts who do not meet the consistency requirement must be excluded, i.e., only consistent judgments contribute to the weighting process. Finally, overall weights, referred to as Global Weights, are derived from the average computation of weights for each consistent judgment of experts. Therefore, Global Weights are established for each criterion and serve as inputs for following the ELECTRE method.

3.3.2. Step 6: ELECTRE

Step 6 implements the ELECTRE I preference aggregation technique, which facilitates the identification of a balanced solution among various alternatives, potentially pinpointing the optimal one in some cases. ELECTRE initiates by constructing a decision matrix, wherein each row represents an alternative ($a \in A$), and each column corresponds to a specific criterion ($i \in I$), which is considered according to its normalised weight ($W_i \in W$). Each entry denotes the performance of a given alternative concerning a particular criterion (i.e., $p_{ai} \in P$). After the decision matrix is established, each criterion is categorised as either a benefit or a cost. The decision matrix is then transformed into a new matrix via utility functions. These utility functions are individually formulated for each criterion based on the original values assigned to each alternative (i.e., $x_{ai} \in X$). These functions could be built in different ways. In this study, among the different formulations, these functions linearly range between a minimum value (0) and a maximum value (1) in alignment with the respective criterion. When a criterion represents a benefit, the utility function's minimum value is 0, and the maximum is 1. Conversely, the highest utility value is attributed to alternatives with the lowest cost for cost-related criteria.

Subsequently, the method proceeds to construct one or multiple outranking relations, which enable a comprehensive comparison of all conceivable pairs of alternatives or options. Specifically, this involves the calculation of concordance and discordance indexes, serving as the basis for an 'elimination' procedure aimed at excluding the less 'satisfactory' alternatives, thereby identifying those that offer a favourable compromise in achieving the ultimate objective. Therefore, these indices indicate the approval and disapproval associated with choosing one alternative over another.

The Concordance index (C) is formed by aggregating the normalised weights $W_i \in W$ of criterion $i \in I$, constituting the collective set of criteria for which alternative $a \in A$ is preferable to $b \in A$. More formally, first the utilities for alternatives $a \in A$ and $b \in A$ are compared together. Next, if $x_{ai} \geq x_{bi}$, the weight of w_i is selected for computing the concordance index C_{ab} for pair of alternatives $a \in A$ and $b \in A$ as in Eq. (3). Vice versa, if $x_{bi} > x_{ai}$, the weight of W_i is selected for computing the concordance index C_{ba}, as in Eq. (4).

$$C_{ab} = \sum_{i \in I: x_{ai} \geq x_{bi}} W_i; \forall a, b \in A \tag{3}$$

$$C_{ba} = \sum_{i \in I: x_{bi} > x_{ai}} W_i; \forall a, b \in A \tag{4}$$

The Discordance index (D) represents the highest value of the greatest difference in utility for each criterion $i \in I$, favouring alternative $b \in A$ over $a \in A$ (and vice versa). Therefore, the computation of D consists of applying the Eq. (5) (if $x_{bi} \geq x_{ai}$) and 6 (if $x_{ai} \geq x_{bi}$), as follows:

$$D_{ab} = \max_{i \in I: x_{bi} \geq x_{ai}} \left(\frac{x_{bi} - x_{ai}}{\max_{a \in A}(x_{ai}) - \min_{a \in A}(x_{ai})} \right); \forall a, b \in A \tag{5}$$

$$D_{ba} = \max_{i \in I: x_{ai} \geq x_{bi}} \left(\frac{x_{ai} - x_{bi}}{\max_{a \in A}(x_{ai}) - \min_{a \in A}(x_{ai})} \right); \forall a, b \in A \tag{6}$$

Next, determining the best feasible compromise solution involves leveraging the combined outranking relationship provided by the Concordance and Discordance indexes, respectively. Precisely, considering each pair of alternatives, $a \in A$ is considered better to $b \in A$ if the value of C_{ab} is close to 1. Conversely, when D_{ba} is close to 1, $b \in A$ is preferable to $a \in A$. However, to unify the direction of information, it can be argued that $a \in A$ is preferred to $b \in A$ if C_{ab} is close to 1 and D_{ab} is close to 0. For alternative selection, a pair of threshold values for C and D must be established, denoted as $\underline{C}$ and $\underline{D}$ respectively. Therefore, they exclude the pairs of alternatives that fall outside this interval.

However, there might be instances where $a \in A$ is preferred to $b \in A$ in the concordance index, whereas $b \in A$ could be preferred to $a \in A$ in the discordance index. In such cases, an outranking indication is not clear. Moreover, these indexes are susceptible to the requirement of establishing threshold values, which could introduce an element of subjectivity. The concepts of Global concordance ($\widehat{C}$) and discordance ($\widehat{D}$) indexes are introduced to mitigate the arbitrary nature of these thresholds. Specifically, these indexes are calculated as indicated in the following Eqs. (7) and (8) across all pairs of alternatives.

$$\widehat{C}_a = \sum_{b \in A: b \neq a} C_{ab} - \sum_{b \in A: b \neq a} C_{ba}; \forall a \in A \tag{7}$$

$$\widehat{D}_a = \sum_{b \in A: b \neq a} D_{ab} - \sum_{b \in A: b \neq a} D_{ba}; \forall a \in A \tag{8}$$

These indexes offer a more comprehensive and standardised measure of preference comparison. The favourable alternative consists of a greater value of $\widehat{C}_a$ and a lower one of $\widehat{D}_a$. Negative results of $\widehat{C}_a$ and positive ones for $\widehat{D}_a$ imply the exclusion of alternative(s) from the ranking.

4. Results and discussion: a tram-train system in Brescia

4.1. The case study

The framework was applied in the Province of Brescia (Italy) to assess the outcomes and reliability of the approach. This was done to draw insights into the varying significance of distinct components, potentially influencing future methods for choosing alternatives in public transport. The case study represents an interesting example for the investigation of the proposed framework applicability for a TT system due to its characteristics and regional configuration. Specifically, the Province of Brescia is the second most populated in the Lombardy Region, with about 1.2 million people and a population density of 264 inhabitants per km^2 (ISTAT, 2023). It serves as a significant industrial, commercial, and social centre in Italy, leading to heavy daily traffic on its roads (Martinelli et al., 2023; Ventura et al., 2023, 2024). Existing railways include several routes (i.e., Milan-Venice, Parma, Cremona, and Iseo-Edolo), which can be integrated into the TT transport system. Fig. 2 illustrates the existing network. The Parma-Brescia is a 92 km railway commuting route not electrified, connecting Parma to Brescia and passing through the Po Valley. Regional plans involve revitalising this route and adding a new track to the close Montichiari airport.

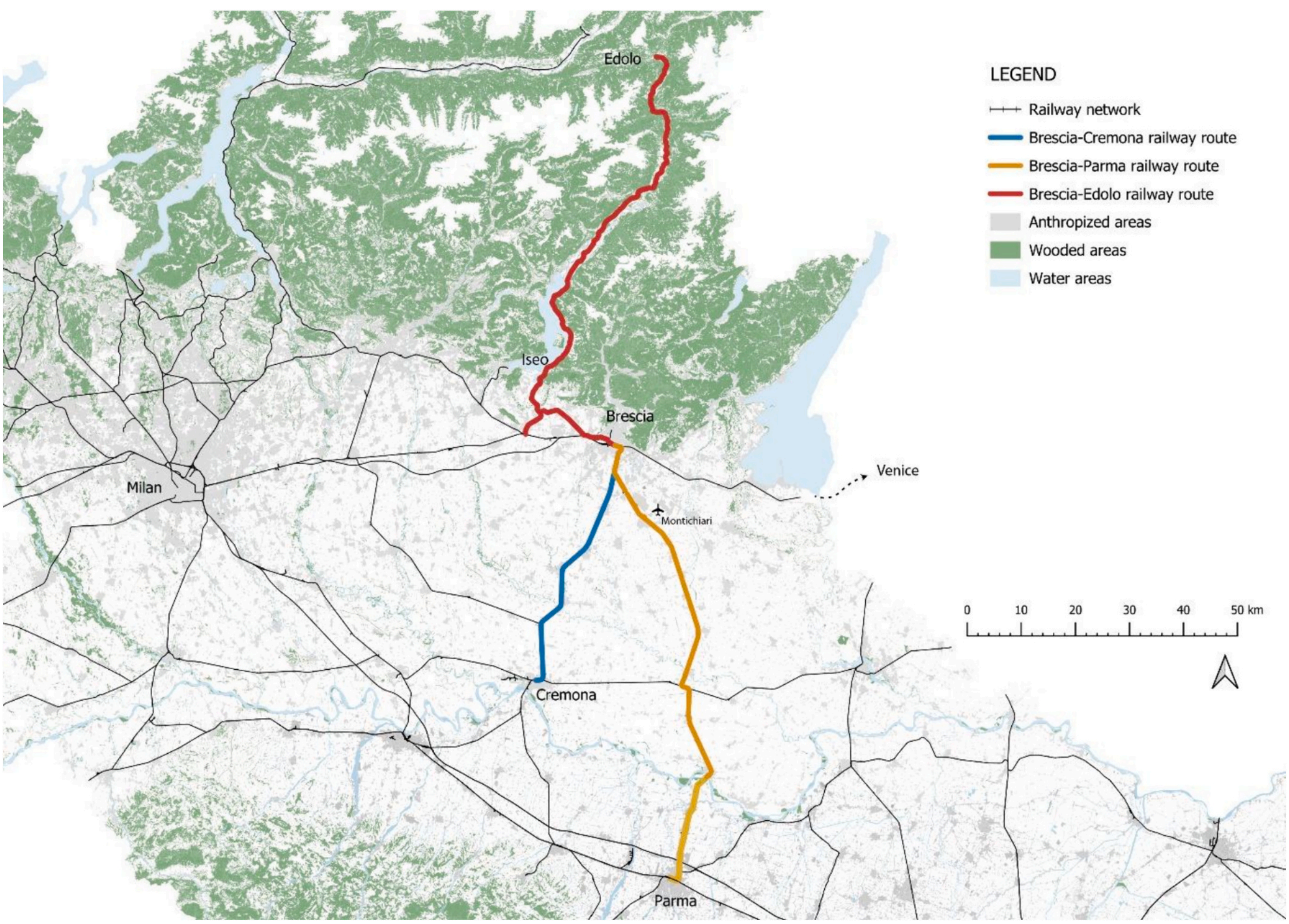

Fig. 2. Study area framework.

Similar features characterise the Brescia-Cremona railway route that connects Brescia to Cremona and serves as a commuting route. Brescia city station also serves the Milan-Venice railway, a national route, while the Brescia-Iseo-Edolo route covers the entire west Province, with 37 stations and a high potential for commuting and tourist traffic.

Simultaneously to potentials, several critical aspects of the lines require intervention, such as limited station capacity and lack of efficient modal interchange, leading to a preference for private vehicles. Additionally, few stops in the urban area result in private vehicles being favoured for short trips. Adopting lighter vehicles like the TT system can mitigate the limited line capacity and suboptimal travel times due to acceleration, braking, and commercial speed issues.

4.2. Phase I. Defining alternatives and judgment criteria

This phase solved two primary objectives: (i) to outline the potential design alternatives that undergo comparison and (ii) to explore the criteria to be integrated into the analysis to identify the most advantageous choice.

Selecting suitable design alternatives (Step 1) is pivotal in generating plausible and viable outcomes. In determining these design options, a range of criteria was carefully chosen to address diverse facets, encompassing economic, environmental, social, and safety considerations. The availability and dependability of the pertinent data following the delineation of the areas under scrutiny influenced the ultimate determination of these criteria. Specifically, four project alternatives were identified that span across the Brescia Province, establishing connections between the city centre and four distinct directrices: North to Concesio (line 1), South to Manerbio (line 4), West-North to Cazzago San Martino (line 2) and West-South to Rovato (line 3) (Fig. 3). The two lines along the western route respectively accommodate the high traffic volumes on the Milan (line 3) and the Iseo-Edolo axis (line 2). The selection was made with a primary focus on achieving the following main goals:

- The reduction of the travel time for the users who currently use the railways (on the routes where the railways already exist).
- The diversion of demand from private to public transport, with direct benefits for both the travellers themselves and society, thanks to a reduction in environmental externalities, including air pollution, greenhouse gasses, noise pollution and road accidents.
- The improvement of the safety level of transport operations on the TT line and in stations.
- The attraction of new traffic demand due to the improved service attractiveness, especially in areas that are currently poorly served.

According to Naegeli et al. (2012), the selected alternatives were categorised into two TT line types, namely A and B (note * of Table 1). Nine main characteristics were utilised to characterise the design alternatives, considering economic, social, and environmental aspects and Naegeli et al. (2012) key requirements for successful systems. Table 1 synthesises the main characteristics and describes the alternatives. Table 1 is self-explicative.

Step 2) of Phase 1 determined criteria to evaluate alternative options, with consideration given to the availability and dependability of the necessary data. This study explored nine objectives (criteria) to ascertain the most promising project hypothesis. The criteria were selected to offer a holistic assessment of the project's feasibility and sustainability, encompassing economic, environmental, social, and safety facets (Battistoni et al., 2019). Generally, the selection followed the main factors of

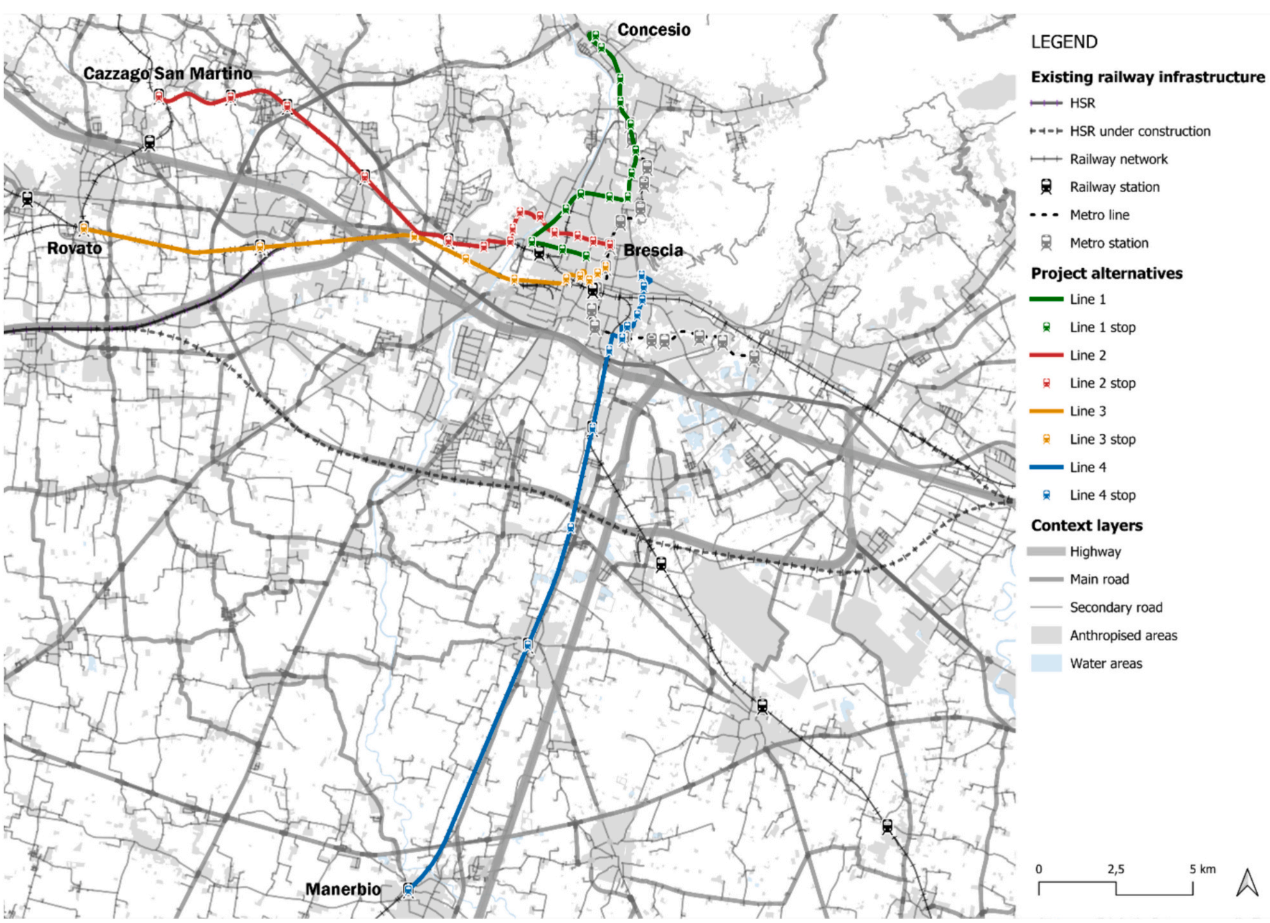

Fig. 3. Project alternatives: lines and stops.

Table 1
The main characteristics of the TT design alternatives.

Design alternatives	Types of TT*	Length	Stops/stations	Existing rail line	Existing infrastructures	Operating vehicles**	Frequency***	Cycle time
	[Text]	*[km]*	*[N.]*	*[km]*	*[%]*	*[N.]*	*[veh/h]*	*[min]*
Line 1	B	12	14	0	0	4	5.0	48
Line 2	A	18	14	13	72	4	2.9	84
Line 3	A	19.5	10	15.5	80	7	5.4	84
Line 4	A	22.5	11	19.6	87	9	5.9	99

Design Alternatives	Description
Line 1	The line serves as a convenient and practical link for daily commuters travelling from Val Trompia to the city (North Directrix), especially during rush hour. Stops are placed approximately every 400–500 m, except for a section along the South bypass where no stops are defined. Piazza Paolo VI is chosen as one of the terminuses due to its importance as a junction for North (Val Trompia-Brescia) and North-West (Val Trompia-Franciacorta) traffic. Piazzale Garibaldi is selected as the opposite terminus as it is a central point in the city that currently lacks adequate public transport service (Fig. 3, green line).
Line 2	The line starts at Bornato Cazzago Station and concludes at San Faustino Underground Station, determining an intermodal point. It follows the existing Brescia-Iseo-Edolo railway line for a portion of its line. The primary objective of the alternative is to offer a swifter and more efficient railway service connecting the city with the Lake Iseo region (West-North). The strategic placement of stops along the railway section ensures convenience, while the frequency of stops increases to every 400–500 m on the section branching off via Val Camonica. This arrangement enables easy west access to the city (Fig. 3, red line).
Line 3	The line departs from the rail station of Rovato to Piazza Vittoria metro station and is shared with the railway with the Milan-Brescia railway for 80% of its total length. Moreover, stops along the railway route have been retained to maintain strategic positioning. The line aims to unload vehicular traffic, especially during peak hours, while enhancing public service with improved frequency, speed, and comfort. The TT line directly connects to the city centre of Brescia (Piazza Vittoria), eliminating the need for passengers to change transportation or walk long distances (Fig. 3, orange line).
Line 4	The line features Manerbio station and Viale Venezia in Brescia as its endpoints. >87% of its length follows the route of the Brescia-Cremona railway. Like other alternatives, it aims to operate parallel to the railway service to alleviate its load and streamline daily road traffic from South Directrix (Manerbio and Bagnolo Mella cities). The stop of Viale Venezia is selected as the terminus because it lacks sufficient public transport service (Fig. 3, blue line).

(*) According to Naegeli et al. (2012), "Type A tram–trains run on the tram tracks in mixed operation with conventional trams and on the heavy rail track in mixed operation with conventional heavy rail trains"; "Type B describes a system in cities without an existing tram network. The TTs do not run in mixed operation with trams on the centre city network; instead, they run in mixed operation with heavy rail trains on the heavy rail tracks".
(**) Estimated as lap time/headway.
(***) Estimated as maximum user flow/vehicle capacity (with load factor equal to 0.8–0.9 depending on the line). Moreover, since the availability of capacity is a crucial aspect of implementing a TT system, it is checked for the railway lines proposed for the TT routes. This was performed by comparing the capacity (or potentiality) values suggested by CIFI (2024) with the associated demands. The former depends on the railway line's technical characteristics (e.g., number of tracks, type of signalling system, number of speed levels), while the latter is the sum of the train scheduled rides with the TT design frequencies during peak hours. The results in Table A1 in the Appendix demonstrate that capacity verifications were fulfilled for all design alternatives.

Table 2
Criteria selected to compare the design of alternatives.

Criteria	Description
Demand	Transport demand assessment relies on calculation models, surveys, or existing studies. The output is an O/D matrix detailing the demand estimation method, survey reference year, and study perimeter. The projected demand is divided into current, TT-generated, and shifted demand.
Number of stops/stations	Choosing the position and number of stops is crucial for the TT, as stops provide access to the service. The stop location criterion strongly influences potential users, with stops in built-up areas having more potential users than those in low-density suburbs.
Investment costs	It covers all project expenses, with the total investment cost provided and divided by construction years and activity type. Cost forecasts extend over the thirty-year time horizon, reflecting the useful life of the project and its components' physical deterioration.
Operating costs	It includes operating and maintenance costs. For each year of system operation, personnel costs, route and vehicle maintenance, and energy consumption are considered. The management costs provide an overview of the system's economic phase and highlight the budget's weak points, i.e., waste and excessive expenses. This enables one to act accordingly by remedying them quickly.
Adaptability of existing infrastructure	It considers the infrastructure that is already present and usable along the route of the project. By infrastructures, we mean all the elements that make up the railway, as well as elements. Such as stations, stops, and depots. Advantages are linked to existing infrastructure and the consequent reduction of project costs, soil consumption, and land use incompatibilities.
Greenhouse Gas Emissions	It considers the decrease in greenhouse gas emissions (GHG) into the atmosphere either directly or indirectly linked to the reduction of car circulation captured by TT service. Indeed, a TT system has a much lower GHG rate than the usual means of transport. Therefore, the criterion represents a benefit of the design alternative since the reduction contrasts global warming and climate change.
Pollution emissions	It considers the decrease in emissions of localised air pollutants (e.g., nitrous oxide, sulphur dioxide, small particulate matter) linked to the reduction of car circulation captured by TT service. Indeed, a TT system has a much lower pollutant emission rate than the usual means of transport. Therefore, the criterion represents a benefit of the design alternative since the reduction is associated with lower impacts on human health and ecosystems.
Noise emissions	It considers the decrease in noise pollution linked to the reduction of car circulation captured by the TT service. Indeed, TT systems have proven to be much less noisy than the traffic generated by private transport. Therefore, the criterion is considered a benefit of the design alternative (Cavallaro and Nocera, 2022).
Road safety	The criterion is linked to reducing road traffic crashes. Therefore, it is calculated as a function of the decrease in car traffic linked to an increase in users' use of the TT service. The computation can be done in general terms over the territory or targeted to the roads directly affected by the TT system.

Cost Benefit Analysis that consider issues on technical feasibility and environmental sustainability (i.e., demand, project options and technical design, environment and climate change considerations, cost estimates and implementation schedule). Therefore, the criteria were derived from previous literature (e.g., Ventura et al., 2022) and technical guidelines (European Commission, 2014; MIT, 2017). Table 2

Table 3
Example of the survey.

Criteria 1	Rating scale								Criteria 2
Investment costs	5	4	3	2	1	2	3	4	5	Number of stops
Number of stops	5	4	3	2	1	2	3	4	5	Demand
Operating costs	5	4	3	2	1	2	3	4	5	Road safety

Table 4
The adjusted semantic scale rating scale.

Intensity	Judgment	Explanation
1	Same importance	Two criteria contribute equally to the objective
2	Low importance	Intermediate situation between 1 and 3
3	Medium Importance	Experience and judgments slightly favour one criterion over the other
4	More than moderate	Intermediate situation between 3 and 5
5	Strong importance	One criterion is strongly favoured over the other

details the list of criteria chosen to establish a foundational framework.

4.3. Phase II. Interactive phase

Steps 3 and 4 of the interactive phase involved conducting a web-based survey among experts selected based on the context of the case study and their diverse perspectives on transport planning and urban and regional planning. Twenty-two highly skilled stakeholders were selected from the Italian context, comprising practitioners (i.e., individuals from public administration, including city, provincial, and regional planners and transport agency representatives) and academics (i.e., professors and researchers in the transportation and urban planning fields). This selection was made to ensure the credibility and reliability of their responses in addressing real-life issues. The survey was managed using the Qualtrics XM platform, ensuring respondents' anonymity. It used a pairwise comparison approach with an adjusted Saaty's Semantic Scale, ranging from 1 to 5 points, to evaluate each criterion. Some examples were reported in Tables 3 and 4.

While 22 experts might seem limited, it was considered sufficient due to the complexity of the topic, the required diversity of opinions, and the depth of analysis needed. Indeed, in Italy, TT systems are not highly widespread, so this sample was deemed representative of a broad range of expertise and perspectives. However, to further address concerns about sample size and enhance the validity and robustness of the results, the dataset underwent expansion by applying a Monte Carlo Simulation (MCS). This technique enabled the original data to be augmented with a larger set of 100 simulated questionaries, ensuring that the data produced by the simulation would be as reliable as those obtained from actual trials. This dual approach of expert judgment and statistical simulation provided a comprehensive foundation for the validity of the findings.

4.4. Phase III. Data processing and ranking

4.4.1. AHP results

In Step 5), the AHP was employed, and with the assistance of the highly skilled stakeholders and MCS, a hierarchy of importance was obtained for each criterion, i.e., their weight. Specifically, the weights for each item were calculated using Eq. (1) for each expert. The sum of weights totalled 1 for each expert. Eq. (2) was used to assess the responses of each expert and ensure the consistency of their responses. This process was repeated for all criteria and experts interviewed. Results for the 22 highly skilled stakeholders were summarised in Table 5, which is self-explanatory and displays the variations in expert opinions concerning the investigated criteria. Conversely, results for the 100 simulated questionnaires were summarised in Table A2 in the Appendix for conciseness.

Next, the Global Weights were computed by aggregating the average

Table 5
Weights of criteria according to the 22 highly skilled stakeholders in the Brescia context.

Questionnaire ID	Expert class	Demand	Number of stops/ stations	Investment costs	Operating costs	Adaptability of existing Infrastructure	Greenhouse Gas Emissions	Pollution emissions	Noise emissions	Road Safety
EQ1	P	0.060	0.046	0.028	0.029	0.108	0.211	0.194	0.180	0.144
EQ2	P	0.090	0.073	0.028	0.046	0.026	0.152	0.170	0.130	0.287
EQ3	P	0.069	0.066	0.030	0.153	0.066	0.194	0.145	0.125	0.152
EQ4	P	0.045	0.060	0.030	0.084	0.041	0.355	0.264	0.017	0.105
EQ5	P	0.106	0.084	0.084	0.155	0.133	0.155	0.144	0.062	0.078
EQ6	P	0.303	0.078	0.116	0.135	0.071	0.072	0.055	0.049	0.121
EQ7	P	0.308	0.051	0.157	0.223	0.108	0.025	0.074	0.018	0.035
EQ8	P	0.116	0.072	0.065	0.065	0.181	0.211	0.131	0.048	0.112
EQ9	P	0.296	0.145	0.143	0.021	0.025	0.044	0.089	0.068	0.168
EQ10	P	0.171	0.016	0.215	0.143	0.297	0.034	0.023	0.020	0.081
EQ11	A	0.105	0.073	0.076	0.076	0.083	0.167	0.167	0.051	0.200
EQ12	A	0.074	0.106	0.034	0.102	0.140	0.164	0.140	0.089	0.151
EQ13	A	0.074	0.106	0.034	0.102	0.140	0.164	0.140	0.089	0.151
EQ14	A	0.054	0.028	0.037	0.028	0.074	0.196	0.196	0.181	0.206
EQ15	A	0.156	0.122	0.060	0.147	0.154	0.042	0.071	0.023	0.224
EQ16	A	0.132	0.105	0.053	0.065	0.210	0.132	0.132	0.047	0.122
EQ17	A	0.167	0.063	0.083	0.144	0.214	0.074	0.093	0.054	0.109
EQ18	A	0.157	0.139	0.081	0.085	0.200	0.099	0.134	0.029	0.078
EQ19	A	0.147	0.142	0.187	0.049	0.075	0.091	0.077	0.047	0.185
EQ20	A	0.047	0.060	0.118	0.080	0.067	0.157	0.157	0.157	0.157
EQ21	A	0.141	0.125	0.055	0.047	0.037	0.105	0.105	0.083	0.303
EQ22	A	0.210	0.180	0.081	0.060	0.048	0.137	0.131	0.078	0.075

P: Practitioners; A: Academics.

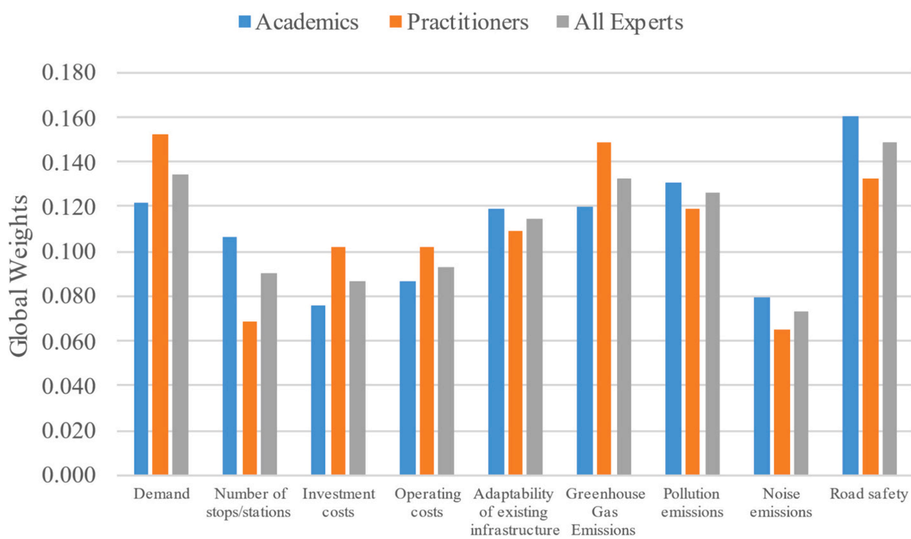

Fig. 4. Global Weights for practitioners, academics, and all experts.

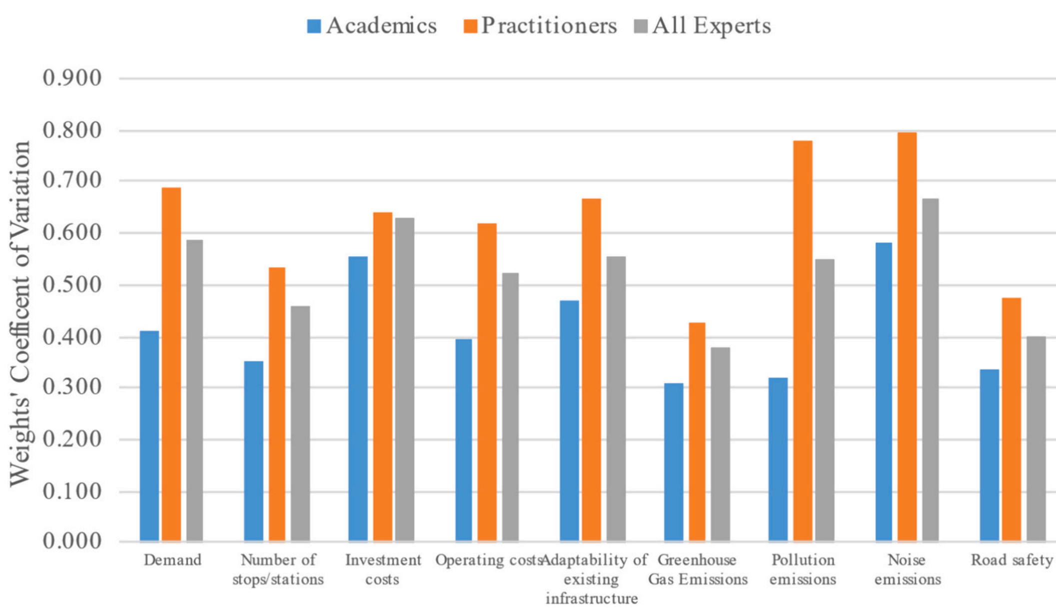

Fig. 5. Coefficients of Variation computed on weights for practitioners, academics, and all experts.

criteria weights for practitioners, academics, and "all experts",[1] considering both experimental and simulated questionnaires. The findings are shown in Fig. 4.

Results revealed that, on the one hand, academics assign relatively higher weights to criteria associated with societal and environmental impacts, such as road safety (0.161) and pollution emissions (0.131). This suggests a strong emphasis on sustainability and public welfare in their decision-making process, which has implications for the liveability of urban space and lower social spending. On the other hand, practitioners prioritise criteria related to practical implementation and operational efficiency, as evidenced by their relatively higher weights for demand (0.152), investment costs (0.102), and operating costs (0.102). These results indicate a focus on meeting current demand while ensuring cost-effectiveness and operational feasibility. Considering "all experts", the findings demonstrate a balanced approach with relatively stable weights across most criteria. This indicates a holistic perspective that integrates both theoretical insights and practical considerations in decision-making processes. Emphasis was given to road safety (0.149), demand (0.135), environmental considerations like greenhouse gas emissions (0.132) and pollution emissions (0.126), and practical aspects such as the adaptability of existing infrastructure (0.115).

The greater importance placed on road safety and demand is somewhat expected. For instance, De Aloe et al. (2023) highlighted that the reduction in crashes due to the shift in demand from road systems (i.e., cars and buses) was one of the major benefits of the two TT alternatives they proposed for the Brescia case study. Specifically, the incremental benefits from reduced use of the road network and the resulting decrease in road crashes were crucial for achieving a positive cost-benefit analysis outcome. Similarly, Ventura et al. (2022) found that the marginal cost of road crashes and the shift in demand from road systems were the variables whose unitary changes had the greatest impact on the economic performance indicators of two TT alternatives analysed in another Italian context.

Next, the Coefficients of Variation (CoVs) for the criteria weights were calculated to provide further insights. The results, summarised in Fig. 5, reveal some intriguing patterns.

[1] "All experts" includes the answers of both academic and practitioners.

Academics display the lower variability, indicating greater consensus regarding the importance of various criteria. This may be due to their reliance on standardised methodologies and theoretical frameworks, leading to more uniform evaluations. Specifically, atmospheric emissions and road safety criteria have the lowest CoVs, highlighting the strong consensus among academics on environmental and social sustainability issues. In contrast, Practitioners show the higher variability in weight assignments across all criteria compared to Academics. The higher dispersion likely stems from their diverse practical experiences and perspectives on the TT system, resulting in less agreement on the importance of the criteria. This could be regarded as a novel result since prior studies did not point out substantial differences in weight variability between academic and practitioner respondents (e.g., Carra et al., 2022; Castillo and Pitfield, 2010). Nevertheless, for policymakers and planners, understanding these dissimilarities is crucial. The significant variability among Practitioners suggests that their varied insights offer a wide range of practical considerations that might be less evident in academics' evaluations. Balancing these perspectives is essential for developing a more comprehensive and robust planning strategy. Finally, the CoVs for the "all experts" group generally falls between the values for Practitioners and Academics, as expected for a combined group.

4.4.2. ELECTRE results

The ELECTRE method, implemented in Step 6), involved the initial building and configuration of the decision matrix based on compliance. Therefore, the project alternatives were placed in the rows, and the criteria in the columns. Next, the matrix was completed by estimating data referring to the criteria for all the project alternatives. The process for data estimation was different for each criterion, such as the units of measure. However, this method was able to process data from different matrices and have different units of measurement, proving to be a suitable method for the type of analysis.

The *Demand* criterion was estimated by elaborating on the passenger Origin/Destination matrix provided by the Lombardy Region for 2014 (Regione Lombardia, 2014). The data pertained to the peak hours of 7:00–7:59 a.m. and 8:00–8:59 a.m. and included municipalities and neighbourhoods served by the TT lines to ensure the reliability of the estimates. The analysis included all movements in both directions, including travel from terminus to terminus and all intermediate stretches.

Stops and stations in urban areas have been placed at about 400–500 m, while in the areas outside the municipalities, the leading criterion was to maintain the existing stops of the railway network. The decision to follow this approach was made due to the strategic position of existing railway stations outside Brescia, serving every inhabited centre. Adding extra stops in areas without potential users would not have provided any advantages.

The *Investment costs* criterion was estimated by carrying out the breakdown of project costs, following the scheme presented in the Italian Ministry of Infrastructure and Transport Appendix for urban mobility analysis (MIT, 2017). Moreover, the estimation of investment costs related to the required number of rolling stocks for each line was derived from Maternini et al. (2014a) and Maternini et al. (2014b), who used analytical formulas to calculate it (note ** and *** of Table 1). Next, project assumptions of quantities were deduced from De Aloe et al. (2023), i.e., vehicle capacity between 600 and 800 passengers; commercial speed about 35 km/h; cost of rolling stock equal to 3.5 million Euro. Then, all monetary values were actualised to 2024 to account for the financial revaluation (ISTAT, 2024). Finally, the maximum flow was calculated using the O/D matrix.

The *Operating costs* were obtained from the product of the annual number of kilometres travelled and the total cost per kilometre (it was overestimated and assumed equal to 7,00 €/km according to Sinha and Labi, 2011). The criterion included charges for ordinary maintenance (i. e., infrastructure, plant, and rolling stock), energy supply, and the annual personnel cost. Like the Investment costs criterion, the computation of annual mileage was carried out following the Italian Ministry of Infrastructure and Transport Appendix for urban mobility analysis (MIT, 2017).

The *Adaptability of the existing infrastructure* was calculated in terms of the percentage of existing infrastructure compared to the overall project system.

The methodology outlined in MIT (2017) was utilised to compute the reduction of *Polluting emissions* from road traffic. The reduction in emissions is attributed to the fact that potential service users will opt to use the TT instead of other modes of transportation with a more significant environmental impact, such as cars or motorcycles. The resulting value is expressed as annual savings and is determined by adopting the empirical formula proposed for Cost and Benefit Analysis (CBA). Therefore, values resulted as a product for each year (i) of variations in kilometres travelled on different modes of transport (estimated using O/D matrices) and invariants that remain constant over time. Some invariants were set to zero if pollutant emission estimates for a specific mode of transport were not needed for funding applications (e. g., tram, trolleybus).

Similar computations and references concerned the reduction of *Noise pollution* from road traffic, *Greenhouse Gas Emissions* and *Road safety* criteria. They are attributed to the likelihood that individuals who would have otherwise used more negative externalities modes of transportation will instead choose to use the TT for their travel needs.

Next, the decision matrix was completed by including all criteria values per design alternatives and defining the "effect" of each criterion, i.e., if they were a cost (C) or a benefit (B). The decision matrix was translated in terms of utility, which included the values of the utility

Table 6

Decision and utility matrix in terms of compliance.

Alternatives	Demand	Number of stops/stations	Investment costs	Operating costs	Adaptabilityof existing Infrastructure	Greenhouse gas emissions	Pollution emissions	Noise emissions	Road safety
	[pass/h]	*[N.]*	*[M€]*	*[M€/year]*	*[%]*	*[€/year]*	*[€/year]*	*[€/year]*	*[€/Year]*
Line 1	3600	14	168.414	4.126	0	1,255,985.07	394,164.00	485,493.21	392,978.50
Line 2	2100	14	113.497	3.091	72	1,098,986.93	344,893.50	424,806.56	343,856.19
Line 3	2610	10	121.255	6.780	80	1,479,707.41	464,374.46	571,971.68	462,977.79
Line 4	3800	11	128.211	7.322	87	2,485,803.78	780,116.94	960,871.97	777,769.94
Nature of impact	B	B	C	C	B	B	B	B	B
Line 1	0.882	1.000	0.000	0.755	0.000	0.113	0.113	0.113	0.113
Line 2	0.000	1.000	1.000	1.000	0.828	0.000	0.000	0.000	0.000
Line 3	0.300	0.000	0.859	0.128	0.920	0.275	0.275	0.275	0.275
Line 4	1.000	0.250	0.732	0.000	1.000	1.000	1.000	1.000	1.000
Weight*	0.135	0.090	0.087	0.093	0.115	0.132	0.126	0.073	0.149

C = Cost, B = Benefit.

* Computed on "all experts".

Table 7
Concordance and discordance indices for each pair of alternatives. Pairs that fall within the limit value range are bold formatted.

Pairs of alternatives	Concordance Index (C)	Discordance Index (D)
Line 1-Line 2	0.705	1.000
Line 1-Line 3	0.318	0.920
Line 1-Line 4	0.239	1.000
Line 2-Line 1	0.295	0.882
Line 2-Line 3	0.270	0.300
Line 2-Line 4	0.270	1.000
Line 3-Line 1	0.682	1.000
Line 3-Line 2	0.730	1.000
Line 3-Line 4	0.180	0.725
Line 4-Line 1	**0.817**	**0.755**
Line 4-Line 2	0.730	1.000
Line 4-Line 3	**0.820**	**0.128**

function. The most favourable alternative was assigned a maximum value of 1, and the least favourable alternative was assigned a minimum value of 0. The intermediary values were calculated through linear interpolation between the value assigned to each alternative and the relevant criterion. The results of this step are shown in Table 6. It is worth noting that, due to the relatively limited number of experts engaged in the interactive phase, the Global Weights considered in the calculations were those referred to as "all experts", i.e., included the answers of both academics and practitioners.

Thereafter, the concordance and discordance indices for each pair of criteria were calculated according to Eqs. (3), (4), (5) and (6) (Table 7). Next, the analysis of both the indices was performed by setting a pair of limit values for the two indices and discarding all alternatives that did not fall within this range. Therefore, only suitable couples were considered to identify the best compromise alternative. A first pair of generally broad limit values was initially set for $C \geq 0.5$ and $D \leq 0.8$. The results showed a greater compromise of Line 4 on Line 1 and Line 3. Therefore, Line 4 was deemed the most favourable alternative and setting a second pair of more restrictive limit values was not deemed necessary.

The Global concordance ($\widehat{C}$) and discordance ($\widehat{D}$) indexes were computed according to eqns. (7) and (8) to check previous results and mitigate the arbitrary nature of thresholds. Accordingly, the results showed the greatest compromise option of Line 4 (Table 8). Negative results of $\widehat{C}_a$ in Line 1, Line 2, and Line 3 and positive ones for $\widehat{D}_a$ of Line 2 and Line 3 implied the exclusion of Line 1, 2 and 3.

Interestingly, Line 1 was the only alternative excluded by both global indicators (i.e., $\widehat{C} < 0$ and $\widehat{D} > 0$). A possible explanation for this finding might be the limited geographical basin served by Line 1 (i.e., the Valtrompia), which is predominantly urban and lacks an existing regional railway. This contrasts with a key success factor for TT systems, i.e., a strong regional orientation (Naegeli et al., 2012).

The analysis revealed that Line 4 performed well in multiple aspects. By considering the design data presented in Tables 7 and 8, it became evident that Line 4 outperformed Lines 1, 2, and Line 3 in most criteria. Moreover, the length of Line 4 (22.5 km) contributed to higher demand and a reduction in externalities. It also benefits from the highest percentage of existing infrastructure, requiring less intervention during implementation. This result is expected, as one of the main goals of TT service is to maximise the use of existing infrastructure (Naegeli et al., 2012).

Table 8
Global indices.

Alternatives	Global concordance Index ($\widehat{C}$)	Global discordance Index ($\widehat{D}$)	Suitable values [Yes, No]
Line 1	−0.532	+0.282	N
Line 2	−1.330	−0.818	N
Line 3	0.184	+1.378	N
Line 4	1.678	−0.842	Y

5. Conclusions

Expanding light rail-based transit networks is a sustainable solution to mitigate the adverse impacts of individual transportation, aligning with sustainability principles and attracting commuters. The Tram-train (TT) system, which combines railway and tramway infrastructure using specialised light rail vehicles, offers numerous benefits in terms of efficiency, effectiveness, and service quality. However, its interoperable nature introduces technical challenges that make it more complex than conventional systems, potentially deterring cities from adoption. Despite its potential, existing literature on TT systems is limited, focusing mainly on general characteristics, key obstacles, critical vehicle components, and technical and organisational concerns. Descriptive approaches predominated, and cost-benefit analyses lacked depth in exploring alternative TT routes. Notably, there is an absence of analysis assessing the suitability of TT routes in mid-sized cities by Multi-Criteria Decision-Making (MCDM) methods.

To address this gap, this study employed a combined MCDM approach to evaluate the potential viability of the TT system in a mid-sized city. This framework advances the current state-of-the-art by providing initial empirical evidence regarding the feasibility of competing TT routes in such areas. The contribution of this paper lies not in introducing a new methodological approach but in applying existing MCDM methods to the TT system, a subject that has been somewhat overlooked in the literature. By quantitatively evaluating and selecting the most suitable TT routes, this study addresses the gap left by previous research. Moreover, the approach benefits from the input of practitioners and academics who were involved to provide importance to evaluation criteria and Monte Carlo simulation methods to include uncertainty.

Specifically, it applies an integrated MCDM methodology that combines AHP and ELECTRE methods, offering a structured and holistic framework for addressing complex urban transportation challenges. It engaged 22 highly skilled stakeholders from the Brescia context, including practitioners (i.e., individuals from public administration and transport agency representatives) and academics (i.e., professors and researchers in transportation and urban planning). This selection ensured credible and reliable responses, reflecting a holistic perspective that integrates both theoretical insights and practical considerations in decision-making processes. Although this sample might seem limited, to further address concerns about sample size and enhance the validity and

Table A1
Capacity (or potentiality) verification of the railway lines proposed for the TT routes.

Alternative	Technical characteristics	Train frequency [veh/h]	TT frequency [veh/h]	Total frequency [veh/h]	Line capacity [veh/h]	Outcome
Line 1	Single track. One speed level.	0.00	5.00	5.00	5.00	Verified
Line 2	Single track. One speed level.	2.00	2.92	4.92	5.00	Verified
Line 3	Double track. Automatic Block System. Two/three speed levels.	6.00	5.44	11.44	16.00	Verified
Line 4	Double track. Axle Count Block System. Two/three speed levels.	2.00	5.94	7.94	10.00	Verified

robustness of the results, the dataset was expanded using Monte Carlo Simulation (MCS). This technique augmented the original data with 100 simulated questionnaires, ensuring that the simulated data were as reliable as those obtained from actual trials. This dual approach of expert judgment and statistical simulation provided a comprehensive foundation for the validity of the findings.

The results demonstrated the feasibility and applicability of TT systems using a robust MCDM framework, providing a more nuanced and comprehensive assessment. This approach ensures a thorough evaluation of TT alternatives, enhancing the validity and robustness of the findings. Additionally, the study underscores the replicability of the methodology across diverse contexts, presenting a structured approach to evaluate the feasibility of the TT system, potentially enhancing global urban mobility. The widespread adoption of this system holds the potential for significant reductions in emissions, aligning with worldwide initiatives to address climate change and enhance urban environmental quality. Moreover, it lays a strong foundation for advocating the development and widespread adoption of TT systems, harmonising with global initiatives aimed at fostering sustainable, efficient, and interconnected urban mobility solutions. These results are invaluable for guiding city planners and transportation professionals and serve as a baseline for the scientific community in evaluating the applicability of the TT system.

Finally, this study indicates several future developments. Firstly, the relatively low number of experts interviewed during the interactive phase depended on the complexity of the topic, the diversity of opinions required, and the depth of analysis. Future analyses should engage a more extensive and diverse group of experts to deepen the perspective of the study and introduce additional evaluation criteria to ensure a thorough assessment of the broader aspects of the evaluated system. Secondly, although previous research suggested conducting a preliminary context analysis to assess the suitability of introducing a TT system in an area, this was not done for Brescia's territory because existing studies, such as Maternini et al. (2014a) and De Aloe et al. (2023), had already defined the territory as suitable. Nonetheless, future research should incorporate this preliminary analysis to provide a more comprehensive assessment of the area. Thirdly, this study simplified the evaluation of emissions and environmental impacts by (a) relying on ministerial guidelines (European Commission, 2014; MIT, 2017), which categorise emissions generated by cars and public transport only as "internal combustion" or "electric," and (b) basing the case study values on a scenario with electrified TT lines. However, as Boray et al. (2024) suggested, other alternative power systems should also be considered, and a Life Cycle Assessment (LCA) might alter the measurements. Ultimately, the method does not assess the effectiveness of stops but rather the overall line. This could affect the optimisation of economic-financial efficiency and lead to different weightings of the criteria considered, as suggested by L'Hostis et al. (2017). Nevertheless, the method proposed in this study is adaptable for such evaluations; for instance, it can verify alternative station scenarios to reduce costs without significantly compromising accessibility and environmental benefits.

CRediT authorship contribution statement

Nuhamin G. Assefa: Writing – original draft, Investigation, Validation, Visualization. **Martina Carra:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Writing – original draft. **Roberto Ventura:** Writing – review & editing, Data curation, Formal analysis, Visualization. **Anna Richiedei:** Visualization, Writing – review & editing. **Benedetto Barabino:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Project administration, Visualization.

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

Table A2
Weights of criteria according to the 100 simulated questionaries.

Questionnaire ID	Expert class	Demand	Number of stops/ stations	Investment costs	Operating costs	Adaptability of existing Infrastructure	Greenhouse Gas Emissions	Pollution emissions	Noise emissions	Road Safety
SQ1	0.164	0.164	0.116	0.119	0.068	0.087	0.132	0.095	0.098	0.120
SQ2	0.066	0.066	0.094	0.059	0.115	0.279	0.114	0.154	0.000	0.120
SQ3	0.037	0.037	0.059	0.150	0.092	0.082	0.323	0.108	0.067	0.082
SQ4	0.084	0.084	0.075	0.031	0.189	0.038	0.239	0.120	0.127	0.097
SQ5	0.062	0.062	0.147	0.142	0.094	0.143	0.062	0.177	0.000	0.172
SQ6	0.209	0.209	0.000	0.046	0.153	0.186	0.056	0.120	0.022	0.208
SQ7	0.230	0.230	0.070	0.140	0.000	0.000	0.107	0.075	0.189	0.190
SQ8	0.183	0.183	0.054	0.074	0.031	0.163	0.114	0.145	0.121	0.116
SQ9	0.369	0.369	0.031	0.013	0.053	0.095	0.172	0.093	0.075	0.100
SQ10	0.249	0.249	0.018	0.115	0.151	0.143	0.036	0.145	0.038	0.104
SQ11	0.160	0.160	0.116	0.034	0.041	0.156	0.117	0.177	0.097	0.101
SQ12	0.114	0.114	0.047	0.048	0.136	0.117	0.152	0.167	0.091	0.128
SQ13	0.039	0.039	0.051	0.123	0.072	0.115	0.147	0.154	0.060	0.240
SQ14	0.000	0.000	0.201	0.040	0.073	0.274	0.044	0.114	0.063	0.191
SQ15	0.122	0.122	0.083	0.079	0.051	0.093	0.155	0.156	0.046	0.214
SQ16	0.190	0.190	0.038	0.078	0.092	0.185	0.102	0.085	0.095	0.136
SQ17	0.166	0.166	0.096	0.085	0.101	0.174	0.114	0.117	0.017	0.130
SQ18	0.185	0.185	0.117	0.035	0.167	0.091	0.072	0.082	0.054	0.197
SQ19	0.061	0.061	0.048	0.059	0.081	0.209	0.159	0.138	0.064	0.182
SQ20	0.128	0.128	0.145	0.119	0.000	0.129	0.082	0.164	0.057	0.175

(*continued on next page*)

Table A2 (*continued*)

Questionnaire ID	Expert class	Demand	Number of stops/ stations	Investment costs	Operating costs	Adaptability of existing Infrastructure	Greenhouse Gas Emissions	Pollution emissions	Noise emissions	Road Safety
SQ21	0.165	0.165	0.050	0.000	0.242	0.181	0.093	0.065	0.026	0.179
SQ22	0.169	0.169	0.130	0.084	0.054	0.050	0.099	0.116	0.149	0.148
SQ23	0.079	0.079	0.148	0.084	0.045	0.150	0.140	0.098	0.100	0.156
SQ24	0.213	0.213	0.000	0.099	0.087	0.189	0.174	0.107	0.024	0.107
SQ25	0.116	0.116	0.079	0.000	0.079	0.112	0.168	0.152	0.098	0.195
SQ26	0.134	0.134	0.156	0.011	0.068	0.067	0.142	0.118	0.152	0.151
SQ27	0.126	0.126	0.037	0.082	0.190	0.061	0.115	0.232	0.092	0.066
SQ28	0.177	0.177	0.096	0.039	0.096	0.047	0.117	0.167	0.087	0.175
SQ29	0.149	0.149	0.122	0.023	0.069	0.153	0.170	0.152	0.008	0.153
SQ30	0.076	0.076	0.122	0.145	0.045	0.110	0.110	0.113	0.109	0.170
SQ31	0.068	0.068	0.150	0.111	0.100	0.143	0.182	0.135	0.035	0.075
SQ32	0.111	0.111	0.026	0.037	0.138	0.135	0.225	0.130	0.098	0.101
SQ33	0.175	0.175	0.161	0.086	0.039	0.045	0.014	0.168	0.099	0.214
SQ34	0.127	0.127	0.065	0.063	0.063	0.163	0.022	0.225	0.076	0.196
SQ35	0.073	0.073	0.059	0.256	0.004	0.230	0.073	0.000	0.011	0.292
SQ36	0.277	0.277	0.041	0.107	0.142	0.101	0.061	0.114	0.000	0.157
SQ37	0.000	0.000	0.099	0.111	0.215	0.055	0.035	0.216	0.179	0.089
SQ38	0.129	0.129	0.111	0.085	0.090	0.172	0.165	0.096	0.017	0.135
SQ39	0.055	0.055	0.050	0.019	0.129	0.157	0.198	0.206	0.065	0.120
SQ40	0.127	0.127	0.077	0.121	0.124	0.116	0.140	0.117	0.119	0.058
SQ41	0.191	0.191	0.147	0.000	0.158	0.098	0.063	0.211	0.061	0.070
SQ42	0.111	0.111	0.077	0.124	0.154	0.080	0.259	0.040	0.050	0.104
SQ43	0.054	0.054	0.060	0.095	0.108	0.000	0.112	0.126	0.126	0.320
SQ44	0.106	0.106	0.117	0.081	0.113	0.078	0.078	0.126	0.135	0.166
SQ45	0.000	0.000	0.132	0.110	0.085	0.123	0.119	0.180	0.085	0.167
SQ46	0.197	0.197	0.065	0.097	0.094	0.121	0.091	0.147	0.000	0.188
SQ47	0.123	0.123	0.078	0.029	0.055	0.157	0.152	0.094	0.118	0.196
SQ48	0.188	0.188	0.091	0.085	0.093	0.143	0.098	0.064	0.125	0.112
SQ49	0.161	0.161	0.049	0.068	0.077	0.162	0.122	0.070	0.034	0.258
SQ50	0.143	0.143	0.065	0.045	0.123	0.087	0.080	0.157	0.091	0.210
SQ51	0.182	0.182	0.115	0.045	0.048	0.083	0.138	0.135	0.077	0.176
SQ52	0.201	0.201	0.094	0.055	0.101	0.116	0.115	0.102	0.103	0.113
SQ53	0.145	0.145	0.062	0.100	0.118	0.067	0.089	0.152	0.103	0.163
SQ54	0.069	0.069	0.111	0.030	0.102	0.164	0.092	0.136	0.195	0.100
SQ55	0.104	0.104	0.050	0.322	0.027	0.024	0.293	0.000	0.000	0.180
SQ56	0.031	0.031	0.063	0.162	0.101	0.133	0.116	0.118	0.125	0.151
SQ57	0.175	0.175	0.102	0.115	0.040	0.179	0.321	0.000	0.043	0.024
SQ58	0.117	0.117	0.150	0.105	0.064	0.065	0.113	0.165	0.083	0.138
SQ59	0.125	0.125	0.055	0.135	0.131	0.133	0.157	0.088	0.000	0.175
SQ60	0.129	0.129	0.133	0.097	0.078	0.073	0.072	0.233	0.040	0.145
SQ61	0.197	0.197	0.057	0.096	0.063	0.195	0.150	0.160	0.000	0.083
SQ62	0.073	0.073	0.094	0.098	0.117	0.122	0.106	0.072	0.122	0.195
SQ63	0.157	0.157	0.075	0.090	0.075	0.147	0.090	0.124	0.062	0.180
SQ64	0.426	0.426	0.077	0.057	0.082	0.042	0.107	0.060	0.086	0.063
SQ65	0.256	0.256	0.084	0.111	0.078	0.000	0.185	0.107	0.077	0.102
SQ66	0.235	0.235	0.090	0.157	0.056	0.020	0.210	0.100	0.081	0.051
SQ67	0.098	0.098	0.083	0.151	0.022	0.070	0.133	0.089	0.079	0.275
SQ68	0.092	0.092	0.161	0.000	0.116	0.152	0.086	0.117	0.090	0.187
SQ69	0.014	0.014	0.126	0.092	0.084	0.055	0.155	0.114	0.146	0.215
SQ70	0.150	0.150	0.048	0.048	0.077	0.233	0.150	0.093	0.011	0.191
SQ71	0.175	0.175	0.075	0.052	0.122	0.099	0.192	0.182	0.000	0.102
SQ72	0.060	0.060	0.094	0.041	0.102	0.263	0.127	0.070	0.098	0.145
SQ73	0.000	0.000	0.098	0.071	0.025	0.124	0.201	0.188	0.155	0.139
SQ74	0.087	0.087	0.133	0.042	0.090	0.129	0.199	0.148	0.045	0.126
SQ75	0.107	0.107	0.040	0.118	0.100	0.135	0.175	0.208	0.064	0.051
SQ76	0.382	0.382	0.076	0.079	0.000	0.031	0.000	0.190	0.075	0.167
SQ77	0.141	0.141	0.067	0.186	0.202	0.000	0.042	0.238	0.000	0.124
SQ78	0.003	0.003	0.077	0.029	0.033	0.065	0.332	0.142	0.076	0.243
SQ79	0.168	0.168	0.089	0.008	0.121	0.156	0.104	0.189	0.069	0.095
SQ80	0.155	0.155	0.142	0.209	0.130	0.012	0.074	0.161	0.000	0.118
SQ81	0.195	0.195	0.139	0.075	0.072	0.108	0.081	0.099	0.078	0.154
SQ82	0.268	0.268	0.137	0.060	0.052	0.066	0.000	0.027	0.137	0.253
SQ83	0.111	0.111	0.208	0.109	0.101	0.093	0.101	0.085	0.083	0.110
SQ84	0.143	0.143	0.122	0.144	0.021	0.156	0.195	0.062	0.000	0.156
SQ85	0.076	0.076	0.082	0.091	0.149	0.110	0.114	0.092	0.066	0.221
SQ86	0.164	0.164	0.133	0.043	0.092	0.055	0.147	0.102	0.141	0.122
SQ87	0.164	0.164	0.096	0.061	0.066	0.119	0.192	0.131	0.060	0.113
SQ88	0.116	0.116	0.140	0.067	0.046	0.064	0.192	0.131	0.074	0.170

(*continued on next page*)

Table A2 (*continued*)

Questionnaire ID	Expert class	Demand	Number of stops/ stations	Investment costs	Operating costs	Adaptability of existing Infrastructure	Greenhouse Gas Emissions	Pollution emissions	Noise emissions	Road Safety
SQ89	0.180	0.180	0.047	0.101	0.099	0.080	0.293	0.051	0.040	0.109
SQ90	0.000	0.000	0.041	0.235	0.145	0.082	0.096	0.143	0.015	0.244
SQ91	0.199	0.199	0.132	0.062	0.048	0.112	0.143	0.110	0.023	0.171
SQ92	0.118	0.118	0.142	0.101	0.044	0.072	0.070	0.124	0.106	0.223
SQ93	0.033	0.033	0.064	0.099	0.162	0.240	0.115	0.099	0.141	0.047
SQ94	0.090	0.090	0.151	0.066	0.107	0.170	0.110	0.112	0.058	0.135
SQ95	0.180	0.180	0.067	0.091	0.096	0.077	0.102	0.079	0.089	0.218
SQ96	0.085	0.085	0.093	0.093	0.091	0.186	0.180	0.109	0.031	0.131
SQ97	0.087	0.087	0.059	0.080	0.127	0.140	0.108	0.186	0.187	0.026
SQ98	0.015	0.015	0.097	0.083	0.169	0.185	0.013	0.153	0.114	0.172
SQ99	0.186	0.186	0.091	0.145	0.084	0.000	0.253	0.144	0.000	0.097
SQ100	0.079	0.079	0.050	0.201	0.179	0.070	0.224	0.075	0.021	0.101

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