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Evaluation of public transportation sustainability factors in Twin Cities of Pakistan: a DEMATEL analysis

Noman Shaukat[1*], Şenay Sadıç[2] , Emre Demir[3]
[1]Institute of Postgraduate Education, Antalya Bilim University, Antalya,
noman.shaukat@std.antalya.edu.tr, ORCID No: https://orcid.org/0000-0002-2059-6329
[2]Department of Industrial Engineering, Antalya Bilim University, Antalya,
senay.sadic@antalya.edu.tr, ORCID No: https://orcid.org/0000-0003-1855-1946
[3]Department of Civil Engineering, Antalya Bilim University, Antalya,
emre.demir@antalya.edu.tr, ORCID No: https://orcid.org/0000-0003-0013-4482
*Sorumlu Yazar

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Abstract

This study proposes a decision making trial and evaluation laboratory (DEMATEL) approach for the evaluation of public transportation (PT) sustainability factors in Pakistan. The methodology both explores the priorities PT sustainability factors and lists cause and effect groups. After briefly reviewing the related literature, the PT sustainability framework is constructed, and the DEMATEL-based multiple-criteria decision analysis (MCDM) approach is introduced. Our methodology is then applied to evaluate PT sustainability factors in the Twin Cities (Islamabad, Rawalpindi) of Pakistan. A sensitivity analysis is also performed by assigning different weights to decision-makers. The results reveal the following: 1) Traffic congestion, infrastructure and aesthetics are the most prominent factors for PT sustainability. 2) Air pollution, infrastructure, accident damage, affordability, and aesthetics are in the cause group. 3) Traffic congestion, accessibility, and human health impact are consistently in the effect group, emphasizing their secondary nature. Their resolution depends on tackling the problems in the cause group. 4) Although environmental factors such as air pollution emerge as the most significant causal factor, they are ranked lower in significance.

1. Introduction

Transportation serves as a vital pillar of a nation's economy and societal infrastructure. Public transportation (PT) systems play a crucial role by offering viable alternatives to private vehicle usage, thereby mitigating traffic congestion, air pollution, and overall carbon emissions. According to International Energy Agency (IEA), in 2020, the transportation sector accounted for approximately 24% of global carbon dioxide emissions from fuel combustion (Almasi et al., 2021; Güven & Keçeci, 2020). PT not only enhances mobility but also promotes social equity and environmental sustainability through its emphasis on accessibility, affordability, and reliability. In the global pursuit of sustainability, transportation assumes a pivotal role as both an economic driver and a significant contributor to environmental challenges. As societies strive to combat climate change and minimize carbon emissions, PT emerges as a fundamental component of sustainable urban development. By providing efficient alternatives to private vehicle usage, PT systems contribute significantly to the reduction of traffic congestion and air pollution, thus fostering greener and healthier urban environments (Boz & Aras, 2021).

A sustainable transportation system is essential for ensuring urban residents' access to safe and environmentally friendly mobility (Keeble, 1988). Sustainable transportation encompasses modes with minimal environmental impact (Litman & Burwell, 2006), balancing present needs with the requirements of future generations (Yigitcanlar & Dur, 2010). Sustainable mobility options include PT, walking, cycling, carpooling, car sharing, and eco-friendly vehicles (Chandra & Kumar, 2020), which encompass indigenous fuels, electric vehicles, and alternative fuel cars.

Defined by the Brundtland Commission, sustainable development entails meeting present needs without compromising those of future generations (Keeble, 1988). Sustainable transportation ensures current well-being without compromising future prospects, considering parameters such as social and economic access, safety, congestion, and emissions (Himanen et al., 2005). Sustainability of transportation systems is evaluated through the triple bottom line framework which assesses environmental, social, and economic dimensions (Qassem, 2023).

PT plays a pivotal role in advancing sustainability, reducing vehicle travel and emissions while enhancing accessibility and economic efficiency (Valiantis, 2014). Challenges persist in designing efficient systems to mitigate infrastructure expansion, particularly in auto-dependent cities facing congestion, pollution, and health impacts. PT serves as a key tool for integrating sustainability into the transportation sector. As transportation engineering encompasses various subfields, sustainability must be applied comprehensively, including in pavement and design engineering, parking systems, and PT infrastructure, facilitated by intelligent transportation systems (ITS). Schiller & Kenworthy (2017) emphasize PT's significant role in reducing vehicle travel and dependency in cities due to its spatial efficiency and social benefits, leading to positive impacts across various sustainability criteria. Standardized PT facilities can shift public preference towards PT usage, reducing fuel consumption and alleviating traffic congestion. Moreover, PT systems and traffic conditions are important indicators of social sustainability and set the tone for a city's daily life (Zhao et al., 2020). Therefore, we can state that the performance of a city's PT system directly influences its economic, social, and environmental sustainability levels.

This study offers contributions to the field of sustainable PT in developing countries, especially in the context of Islamabad and Rawalpindi which are referred to as Twin Cities of Pakistan. Sustainability of PT systems has a multi-criteria nature and attracts interest in both academy and practice. Several authors developed multiple-criteria decision analysis (MCDM) methods to measure or analyze sustainability factors in transportation (Ramadan & Özdemir, 2022; Velasco Arevalo & Gerike, 2023). While many authors focused on evaluating alternative options for PT (Büyüközkan et al., 2018; Keshavarz-Ghorabaee et al., 2021; Rasca & Major, 2021; Seker & Aydin, 2020), none of the existing methodologies evaluate PT sustainability factors in terms of their prominence and extract cause and effects groups in developing regions. The most commonly used PT sustainability criteria are used in the study, and the factors are validated by references and supported by the opinions of decision-makers.

This paper proposes an MCDM approach to explore the factors in PT sustainability based on the decision making trial and evaluation laboratory (DEMATEL) methodology, which not only provides a cause and effect analysis but also presents the strength of each factor. The proposed methodology is employed to explore the sustainability factors of PT in the Twin Cities. Developed by Battelle Memorial Institute in 1972, DEMATEL can illustrate complex causal interactions and efficiently locates the complicated system cause-and-effect chain components (Gabus & Fontela, 1972). After a literature review in PT sustainability, the most common PT sustainability factors are summarized constructing a PT sustainability framework. Opinions of academic and field experts are incorporated to provide practical insights into the prioritization of factors in sustainability transitions. While this study focuses on Pakistan, its findings are also relevant for other developing nations and can serve as an example to be customized for their own needs.

The following sections begin with a literature review. Subsequently, a detailed explanation of the methodology is provided, which includes a research overview, a framework of sustainable PT, and the steps of the DEMATEL approach. Following this, we present the case study section, which includes information about the Twin Cities and its application. Further on, we list and explain the results and findings, followed by a sensitivity analysis. Finally, the study concludes with final remarks, managerial implications and potential research directions.

2. Literature review

The topic of sustainable PT performance analysis has accumulated a significant body of theoretical and empirical research, incorporating effectiveness, efficiency, economic viability, and environmental implications. For example, a combination of theoretical analysis and real-world policy implementation are required for successful transportation planning (Vreeker & Nijkamp, 2005). Therefore, group decision making and multi criteria approaches are frequently employed to incorporate opinions of various stakeholders (governmental and society, regulators, academicians, and policy makers) to come up with effective sustainable transportation strategies.

Various MCDM methods have been widely utilized in transportation research to assess and prioritize sustainable transportation systems. Awasthi et al. (2011) employed the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to select sustainable transportation systems under uncertain conditions. Similarly, Shabani et al., (2022) devised a framework based on the Best-Worst Method (BWM) and fuzzy technique to evaluate customer satisfaction in PT during the pandemic, focusing on urban areas. Chandra & Kumar (2020) developed an analytical framework to measure the popularity of sustainable transportation modes, such as PT, cycling, and walking, based on sentiment analysis of social media posts. Nassereddine & Eskandari (2017) and Demir et al. (2023) proposed integrated MCDM methods including DELPHI, Group Analytic Hierarchy Process (GAHP), PROMETHEE, and Pythagorean fuzzy-based AHP-VIKOR to evaluate PT systems in urban areas. Lastly, Ghoushchi et al. (2023) introduced a stepwise weight assessment ratio analysis (SWARA), Measurement of Alternatives and Ranking According to Compromise Solution (MARCOS), and spherical fuzzy set-based approach to prioritize sustainable vehicles for urban transportation systems.

DEMATEL method is widely employed in literature for its effectiveness in revealing the relationships among factors within a complex system. By categorizing factors into subgroups, DEMATEL identifies the connections between them (Falatoonitoosi et al., 2014). DEMATEL-based studies assess cause-and-effect relationships among numerous factors and prioritize them. (Chirra & Kumar, 2018; Fu et al., 2012; Kijewska et al., 2018). Yang & Tzeng (2011) incorporated DEMATEL with Analytic Network Process (ANP), and zero-one-goal programming (ZOGP) to assess the sustainability of transportation infrastructure initiatives. Nawaz & Ali (2020) investigated the link between social, behavioral, and active transport in Pakistan using DEMATEL. Moreover, Trivedi et al. (2021) employed DEMATEL to examine barriers in implementing waterways as a sustainable transportation mode. Besides the studies mentioned above, DEMATEL finds application in diverse fields such as supply chain management, quality control sorting, analysis of sustainable barriers in transportation, industrial management, and entrepreneurship evaluation.

MCDM methodologies are also applied in decision making processes within Pakistan. For example, Nawaz & Ali (2020) explored the relationship between social, behavioral, and active transport in the country using DEMATEL. Additionally, Ullah et al. (2018) utilized an Analytic Hierarchy Process (AHP) based approach to prioritize gaseous alternatives for Pakistan's road transport sector. Then, Solangi et al. (2021) assessed renewable energy barriers in Pakistan employing the fuzzy TOPSIS method, highlighting the role of governmental policies in overcoming these obstacles. Moreover, Raza et al. (2022) integrated traffic simulation software, fuzzy AHP, TOPSIS, and VIKOR methods to determine optimal strategies for establishing a more sustainable transportation system in Pakistan.

Although MCDM has been widely applied in decision making processes within Pakistan and in assessing transportation factors, no existing methodologies, to the best of our knowledge, have prioritized PT sustainability factors. Additionally, none have provided a cause-and-effect analysis in developing regions, particularly in cities across Pakistan.

3. Methodology

The methodology employed in this paper includes the construction of a PT sustainability framework and the utilization of the DEMATEL methodology. Initially, the research overview is provided to guide our methodology. Subsequently, the PT sustainability framework, discovered after a brief review of the literature, is presented. Finally, the DEMATEL approach is explained, highlighting its primary applications and providing its steps and relevant mathematical formulations.

3.1. Research overview

Figure 1 presents the methodology flowchart with the steps of the methodology. Initially, key factors of sustainable PT are identified, after a brief literature review. The constructed PT sustainability framework is used in DEMATEL methodology as factors. Then, two industrial and three academic experts are selected to participate in the questionnaire process. Their individual responses are evaluated using the DEMATEL approach's linguistic scale to understand the interrelationships among factors. After implementing the steps of DEMATEL, cause and effect groups among sustainability factors are determined. Moreover, factors are ranked based on their priority which can guide decision-makers on where to allocate resources effectively. Finally, a sensitivity analysis is conducted by changing the priority of decision-makers.

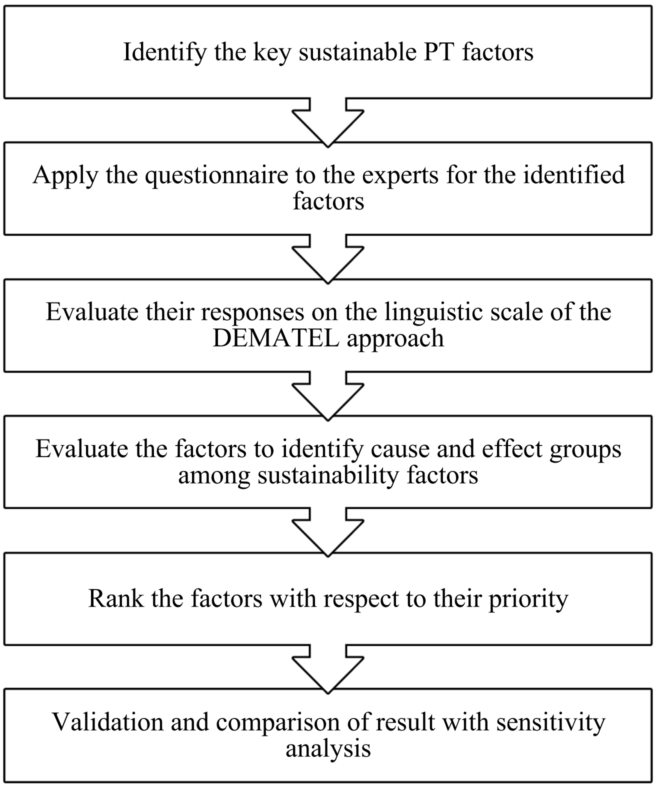

Figure 1. Methodology flowchart

3.2. Framework of sustainable public transportation

Various studies have been conducted to develop indicators and decision making models to support sustainable transportation planning and policy-making. For instance, Litman and Burwell (2006) evaluate factors affecting transportation sustainability across environmental, societal, and economic dimensions. Jeon et al. (2010) introduce a composite sustainability index as a decision support tool for transportation policymaking and employ an MCDM approach to evaluate transportation and land use plans in Atlanta. In PT system sustainability assessment, Bongardt et al. (2011) integrate social, economic, and environmental indicators, while Haghshenas and Vaziri (2012) develop a sustainable transport index to rank countries' transportation systems based on environmental, social, and economic factors. Karjalainen & Juhola (2019) presented the Public Transportation Sustainability Indicator List (PTSIL), applying it to policy documents from Finland and Canada. Afrin & Yodo (2020) provide an overview of existing road traffic congestion measures and suggest ways to develop a sustainable and resilient traffic management system. Kraus & Proff (2021) systematically review and analyze sustainable transportation criteria, constructing a hierarchical framework for measuring sustainability elements. Al-lami & Torok (2023) conduct a literature review proposing future directions for sustainable transportation, summarizing key transportation sustainability indicators. Hou et al. (2023) define PT sustainability, explaining the mechanism of sustainable development in urban PT and creating an index system and evaluation model to assess PT sustainability in 36 major Chinese cities. Finally, Velasco & Gerike (2024) develop the Sustainable Public Transport Index for Latin America (SPTI-LATAM) to address all relevant sustainability aspects of PT systems in the region, employing it directly in eleven case study cities.

Table 1 lists a selected list of factors influencing the sustainability of PT systems, categorized under economic, environmental, and social dimensions. In literature, sustainability factors are diverse and sometimes vague and repetitive. Therefore, this list is established by including the most common factors, supported by the opinions of decision-makers. Each factor is defined alongside its corresponding code and elaborated with references. The environmental dimension encompasses water pollution, noise pollution, and air pollution, while the economic dimension includes traffic congestion, accessibility, infrastructure, consumer cost, and accident damage. The social dimension covers equity, affordability, human health impact, community cohesion and liveability, and aesthetics. Additionally, each factor is described.

Table 1. Factors affecting public transportation sustainability

Pillars	Factors	Description	References
Economic	Traffic Congestion (EC1)	Traffic congestion (EC1) refers to the condition in which vehicles on a road experience delays due to excessive volume of road users and infrastructure capacity limitations.	(Afrin & Yodo, 2020; Litman & Burwell, 2006)
	Accessibility (EC2)	Accessibility (EC2) mentions the ease in using PT services considering several factors such as the frequency of departures, waiting time, proximity of transportation options, and coverage of service points.	(Afrin & Yodo, 2020; Al-lami & Torok, 2023; Litman & Burwell, 2006)
	Infrastructure (EC3)	Infrastructure (EC3) of a PT system refers to the prior investment and development including the construction and maintenance of roads, bridges, stations, stops, and facilities.	(Kraus & Proff, 2021; Litman & Burwell, 2006)
	Consumer Cost (EC4)	Consumer cost (EC4) designates the ratio of total expenses over total revenue in PT systems.	(Al-lami & Torok, 2023; Bongardt et al., 2011; Hou et al., 2023; Karjalainen & Juhola, 2019; Kraus & Proff, 2021; Litman & Burwell, 2006; Velasco & Gerike, 2024)
	Accident Damage (EC5)	Accident damage (EC5) states the consequences of accidents occurring in PT systems which can negatively affect public health and safety, and lead to economic losses.	(Jeon et al., 2010; Litman & Burwell, 2006)
Social	Equity (SC1)	Equity (SC1) mentions the fairness of PT systems via several factors such as ease of boarding, seating availability, and discrimination prevention and promoting inclusivity regardless of background and circumstances.	(Al-lami & Torok, 2023; Jeon et al., 2010; Kraus & Proff, 2021; Litman & Burwell, 2006; Velasco & Gerike, 2024)
	Affordability (SC2)	Affordability (SC2) in PT systems denotes the cost of using services relative to individual or household income, assessed by factors like monthly PT expenses and average household income.	(Haghshenas & Vaziri, 2012; Kraus & Proff, 2021; Litman & Burwell, 2006; Velasco & Gerike, 2024)
	Human Health Impact (SC3)	The human health impact (SC3) of PT refers to its effects on the physical and mental health of individuals, which include the effects of pollution, physical activity or inactivity, and exposure to accidents in PT systems.	(Al-lami & Torok, 2023; Hou et al., 2023; Jeon et al., 2010; Karjalainen & Juhola, 2019; Kraus & Proff, 2021; Litman & Burwell, 2006)
	Community Cohesion and Liveability (SC4)	Community cohesion and liveability (SC4) defines the strength and quality of relationships within a community and the establishment and existence of PT facilities and amenities that support a high quality of life and foster a sense of community.	(Al-lami & Torok, 2023; Jeon et al., 2010; Litman & Burwell, 2006)
	Aesthetics (SC5)	Aesthetics (SC5) in PT systems refers to the enjoyment, comfort, and leisure experienced by individuals while traveling on PT, including design and ambiance of vehicles and facilities, the quality of PT experience, and the existence of amenities supporting a pleasant journey.	(Al-lami & Torok, 2023; Karjalainen & Juhola, 2019; Litman & Burwell, 2006)
Environmental	Water Pollution (EN1)	Water pollution (EN1) defines the contamination of water bodies such as rivers, streams or sea associated with the operation and infrastructure of PT systems.	(Hou et al., 2023; Litman & Burwell, 2006)

Noise Pollution (EN2)	Noise pollution (EN2) refers to the excessive traffic noises caused by PT systems that can lead to numerous adverse diseases.	(Jeon et al., 2010; Kraus & Proff, 2021; Litman & Burwell, 2006)
Air Pollution (EN3)	Air pollution (EN3) describes the release of harmful and toxic substances into the atmosphere originated from PT systems.	(Al-lami & Torok, 2023; Hou et al., 2023; Kraus & Proff, 2021; Litman & Burwell, 2006; Velasco & Gerike, 2024)

3.3. DEMATEL approach

DEMATEL is a matrix-based causal modeling technique developed to analyze complex systems by identifying the relationships between multiple factors (Ciptomulyono et al., 2022). The method aims to determine the relative influence of each factor on the system by analyzing interdependencies, causal relationships, and the directionality of these relationships. It is particularly effective for handling complex systems with numerous interrelated factors. (Díkmen & Taş, 2018; Falatoonitoosi et al., 2014). DEMATEL technique includes six main steps, given below (Rajak et al., 2021).

Step-1 *- Determine the experts*
Since DEMATEL is based on expert opinion and evaluation, experts related to the problem are selected and contacted at this step.

Step-2 *- Design linguistic scale and compute initial relation matrices*
For the designed problem, n factors are identified, and H decision-makers are asked to evaluate the direct influence of each factor on one another, using a linguistic scale (Table 2). The scores for the evaluation of the direct influence of each factor on one another are provided by experts, resulting in the creation of an $n \times n$ non-negative matrix, represented as $H^1, H^2, \dots, H^n$. The average relation matrix is calculated based on the initial relation matrices by giving equal weight to each decision-maker. In the extension of the analysis, different weights are given to different decision-makers. Therefore, we calculate the weighted relation matrix instead of the average relation matrix in the sensitivity analysis. The related weight for each decision-maker is used to find the weighted relation matrix.

Table 2. Linguistic scale for expert evaluation

Variable integer	Scale
0	No influence
1	Low influence
2	Medium influence
3	High influence

Step-3 *- Design normalized direct relation matrix*
The total of all the matrix's rows and columns is computed to normalize. The value k is used to denote the biggest sum of the row and column sums. Each direct-relation matrix element must be divided by k to calculate the normalized direct-relation matrix.

$$k = \max\left\{max\sum_{j=1}^{n} x_{ij}\,, max\sum_{i=1}^{n} x_{ij}\right\} \tag{1}$$

$$D = \frac{1}{k}X \tag{2}$$

In the DEMATEL process, matrix H depicts direct impacts among criteria. Row sums show the total impact of criterion i on others, while column sums indicate the total impact received by criterion j from others. The highest impact is identified by the maximum value in each column. To ensure consistency, matrix H is normalized, yielding matrix D with elements between 0 and 1, crucial for accurate weighting and balance.

Step-4 *- Calculate total-relation matrix*
The calculation of the total-relation matrix is performed once the normalized matrix is obtained, where I is identity matrix and T is total-relation matrix in Eq. (3).

$$T = D(I - D)^{-1} \tag{3}$$

Step-5 - *Compute* $r_i + c_j$ & $r_i - c_j$
At this step, r_i & c_j are computed by the row sum and column sum respectively.

$$r_i = \sum_{j=1}^{n} T_{ij} \tag{4}$$

$$c_j = \sum_{i=1}^{n} T_{ij} \tag{5}$$

The vector r_i represents the comprehensive impact of criterion i on other criteria $j = 1, 2, \dots, n$, combining both direct and indirect effects. Similarly, c_j denotes the comprehensive impact criterion j receives from other criteria $i = 1, 2, \dots, n$. "Prominence" (P_i) is computed as the sum of r_i and c_j (when $i = j$), reflecting the significance of criterion i in the system and providing an index of its total impact. Conversely, "Relation" (R_i) equals the difference between r_i and c_j, indicating the net impact of criterion i on the system. A positive value of $r_i - c_j$ implies criterion i is a causal factor, while a negative value suggests it is an influenced or dysfunctional factor.

Step-6 - *Calculate threshold value*
The threshold value (θ) is established by calculating the average values of the matrix T to eliminate minor impacts. θ enables focusing on the most significant relationships in the system.

4. Case study

Designing a sustainable PT system is a global task, but developing countries encounter specific challenges in infrastructure expansion and decision making. In this context, evaluation of the PT sustainability factors in the Twin Cities is considered as a case study. Islamabad and Rawalpindi, referred to as the Twin Cities, experience air pollution and traffic problems, leading to fatal accidents. Next, we provide a detailed introduction to the Twin Cities, followed by an application of the DEMATEL methodology for prioritization and cause-and-effect analysis of PT sustainability factors.

4.1. Twin Cities, Pakistan

Figure 2 depicts the geographical location of Twin Cities, Islamabad (North 33.7294°, East 73.0931°) and Rawalpindi (North 33.5984°, East 73.0441°). While Islamabad covers 906.5 km^2, 25% of which is urban, and has a population of 2 million, Rawalpindi boasts a population density of 8,100 people per km^2. The demand for transportation has surged in both cities due to population growth driven by migration and increased car ownership. Moreover, the transportation system is further challenged by rising car ownership, fueled by affordable financing options, and the absence of a reliable PT system. Therefore, addressing PT challenges is critical for sustainable development in such urban settlements.

According to NESPAK's 2017 survey, the Regional Transport Authority (RTA) and Islamabad Transport Authority (ITA) oversee PT in both cities, which commands 42% of the market share. These cities offer diverse PT options, including city buses like the Green Line and Orange Line services, and intercity options like motorway buses. These services provide different mode options to commuters in PT.

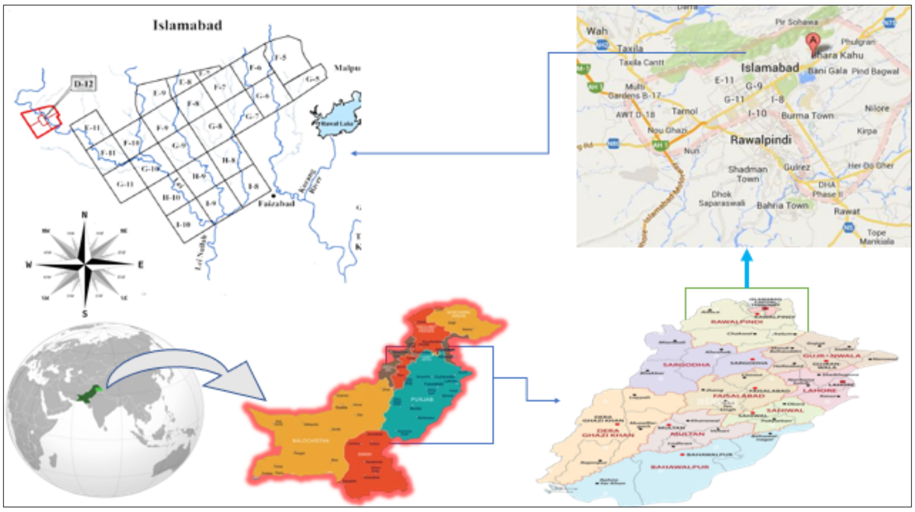

Figure 2. Location of Twin Cities (Source: https://en.wikipedia.org/wiki/Islamabad, https://www.google.com/maps)

4.2. Application

In this section, DEMATEL methodology is applied to explore the priorities of PT sustainability factors in Twin Cities. Moreover, a cause-and-effect analysis of factors is also presented. Figure 3 presents the created PT sustainability framework with all factors defined and associated abbreviations. This framework is used in the DEMATEL application and applied to PT of Twin Cities.

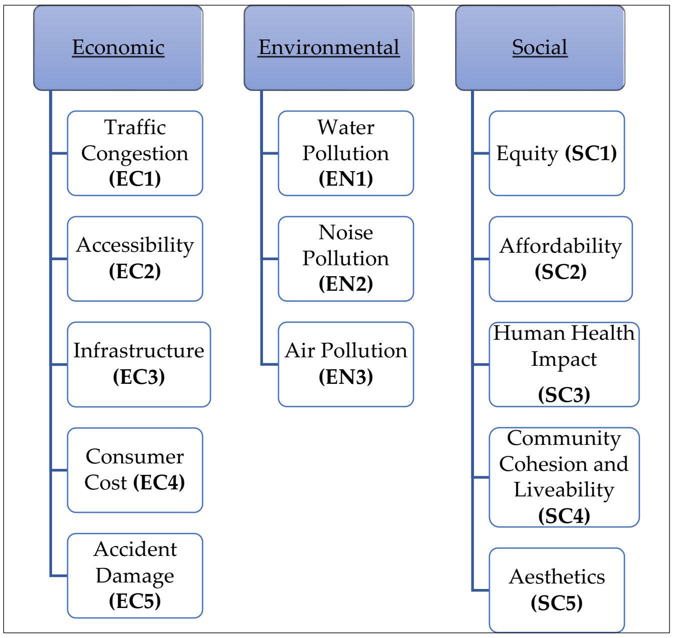

Figure 3. PT sustainability framework

To understand the relationships between sustainability factors, expert opinions are gathered. Five experts have been selected: two field engineers and three academic experts (Table 3). The field engineers are employed by the Public Works Department (PWD), and they are directly involved in the decision making processes of the Twin Cities PT system. Moreover, they witness the challenges and problems of the PT system, directly. The academic experts are also directly involved in PT related research and employed in Twin Cities.

All experts evaluate the direct impact of one factor on another, resulting in five initial relation matrices (13 × 13). The numerical scale as given in the methodology section is employed with integers between 0 and 3. Five initial relation matrices are combined to create the average relation matrix by giving equal weight to all respondents (Appendix A).

Table 3. Details on the experts

Expert	Age	Resident	Occupation
1	50	Twin Cities	Divisional Officer Public Works Department (PWD)
2	32	Twin Cities	Executive Engineer PWD
3	34	Twin Cities	Asst. prof., Department of Transportation Engineering
4	44	Twin Cities	Prof., National Univ. of Science and Tech. (NUST)
5	32	Twin Cities	Asst. prof., Department of Transportation Engineering

Later, the normalized direct relation matrix and the total relation matrix are calculated using Eq. (1), (2), and (3) (Appendix B). Then, the overall prominence ($r_i + c_j$) and the net effect of a factor on the system ($r_i - c_j$) are further determined using Eq. (4) and (5) respectively. r_i and c_j are measures of the direct and indirect influence of each factor on the other factors. Therefore, the results of DEMATEL application are obtained. Finally, the threshold value is calculated as 0.1588.

5. Results

The results of the DEMATEL application are presented in Table 4. $r_i + c_j$ and $r_i - c_j$ metrics are used to understand the relationships between factors. Accordingly, $r_i + c_j$ represents the significance of a factor, where a high value of $r_i + c_j$ indicates that a factor has a strong impact on other factors in the system. On the other hand, $r_i - c_j$ shows whether a factor is a cause or an effect in the system. A positive value of $r_i - c_j$ indicates that the factor is a cause, while a negative value specifies it as an effect.

Table 4. Results of DEMATEL application

Factors	r_i	c_j	$r_i + c_j$	$r_i - c_j$
Traffic Congestion (EC1)	2.612	2.969	5.580	-0.357
Accessibility (EC2)	1.829	2.812	4.641	-0.983
Infrastructure (EC3)	2.509	2.388	4.896	0.121
Consumer Cost (EC4)	1.806	2.165	3.971	-0.359
Accident Damage (EC5)	2.441	1.805	4.246	0.637
Water Pollution (EN1)	1.800	1.703	3.502	0.097
Noise Pollution (EN2)	1.624	1.480	3.105	0.144
Air Pollution (EN3)	1.748	0.920	2.668	0.828
Equity (SC1)	2.007	1.854	3.861	0.154
Affordability (SC2)	2.288	1.859	4.147	0.429
Human Health Impact (SC3)	1.641	2.393	4.034	-0.752
Community Cohesion and Liveability (SC4)	1.980	2.169	4.149	-0.188
Aesthetics (SC5)	2.547	2.318	4.865	0.230

Based on the $r_i + c_j$ values given in Table 4, the factors are ranked for their significance in the following order: EC1, EC3, SC5, EC2, EC5, SC4, SC2, SC3, EC4, SC1, EN1, EN2, and EN3. The findings reveal that traffic congestion (EC1) is the most significant concern, indicating a need for resolution. Accessibility (EC2) and infrastructure (EC3) follow closely behind, highlighting the importance of enhancing transportation infrastructure and ensuring equitable access to PT services. Factors such as consumer cost (EC4) and accident damage (EC5) also feature prominently, underscoring the economic and safety implications associated with PT. Interestingly, while environmental concerns like air pollution (EN3) are recognized, they are ranked lower in significance compared to other factors, suggesting a potential gap in prioritizing environmental sustainability within the PT system.

Moreover, based on the $r_i - c_j$ values, the cause and effect groups of factors are identified. The groups are depicted in Figure 4 (the cause and effect groups diagram). Factors positioned above the horizontal axis have positive $r_i - c_j$ values and construct the cause group: EN3, EC5, SC2, SC5, EC3, EN2, SC1, EN1. Likewise, factors below the axis have negative $r_i - c_j$ values and establish the effect group: EC2, SC3, EC1, EC4, SC4.

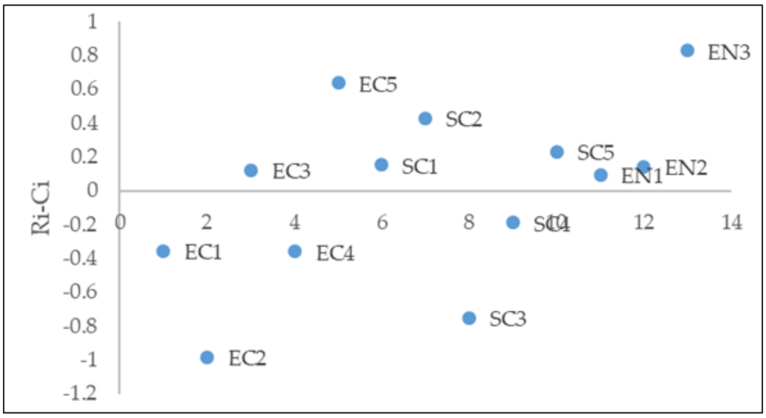

Figure 4. Cause and effect groups diagram

Air pollution (EN3) is ranked as the most important causal factor, indicating the urgent need to address air pollution to promote sustainable transportation. Accident damage (EC5), affordability (SC2), aesthetics (SC5), and infrastructure (EC3) are also among the strong causal factors highlighting the need for investments and innovations in PT system. The effect group constitutes accessibility (EC2), human health impact (SC3), traffic congestion (EC1), consumer cost (EC4), community cohesion, and livability (SC4). These socioeconomic factors are secondary which can be resolved by targeting the cause group.

Figure 5 presents a visual representation of these interrelationships between the factors. In the diagram, each factor is represented as a node and the lines signify the relationship strength between different factors. The figure may help decision-makers to understand the impact of factors and identify areas for improvements to enhance PT sustainability.

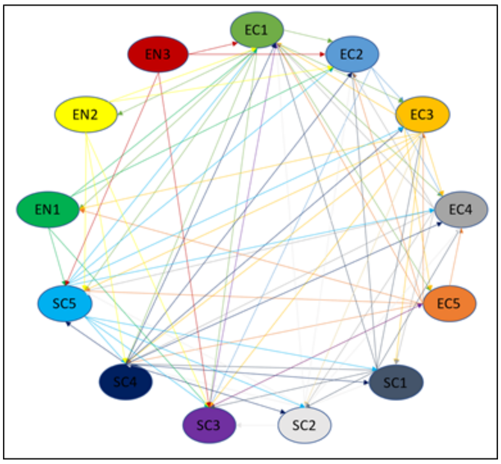

Figure 5. Interrelationship of factors

6. Sensitivity analysis

In our study, we conduct a sensitivity analysis of the DEMATEL approach by allocating different weights to decision-makers. In MCDM methods, the results are highly dependent on the expert opinion. The sensitivity analysis was performed due to anticipated differences in opinions or priorities between academic experts working on theoretical aspects of PT and engineers employed in resolving practical PT-related problems in a developing region. Therefore, six scenarios are presented to understand the differences in the perceptions of academic and field experts (Table 5): Scenario 1 considers equal weight to all decision-makers (20% for each expert) as the default scenario with the results already presented above. Scenarios 2 and 3 favor academic (90%) and field engineering expertise (90%) respectively. Furthermore, Scenarios 4 and 5 favor academic (70%) and field engineering expertise (70%) respectively. In Scenario 6, a more balanced approach is taken, with academic and field engineers assigning equal weights to criteria (50% each).

Table 5. Scenarios for sensitivity analysis

Scenarios	Description	Academic Expert	Field Engineer

Scenario 1	All DMs equal	0.20	0.20	0.20	0.20	0.20
Scenario 2	Academic dominate(90%)	0.30	0.30	0.30	0.05	0.05
Scenario 3	Field dominate (90%)	0.03	0.03	0.03	0.45	0.45
Scenario 4	Academics favored (70%)	0.23	0.23	0.23	0.15	0.15
Scenario 5	Field favored (70%)	0.10	0.10	0.10	0.35	0.35
Scenario 6	Equal weight (50%-50%)	0.16	0.16	0.16	0.25	0.25

In performing the sensitivity analysis, the weighted relation matrices are calculated instead of the average relation matrix, in the second step of DEMATEL. The related weight for each decision-maker is used to find the weighted relation matrix. The results of the scenarios 1, 2, 3 created for DEMATEL analysis are given in Table 6, while the results of the scenarios 4, 5, 6 are given in Table 7.

Table 6. Results of scenarios 1, 2, 3

	Scenario 1			**Scenario 2**			**Scenario 3**		
Rank		$r_i - c_j$	$r_i + c_j$		$r_i - c_j$	$r_i + c_j$		$r_i - c_j$	$r_i + c_j$
1	**EC1**	-0.36	5.58	**EC1**	-0.49	47.98	**EC1**	-0.01	7.69
2	**EC3**	0.12	4.90	**EC3**	0.16	42.40	**EC3**	0.01	6.70
3	**SC5**	0.23	4.87	**SC5**	0.21	42.15	**SC5**	0.31	6.66
4	**EC2**	-0.98	4.64	**EC2**	-0.95	40.23	**EC2**	-1.05	6.32
5	**EC5**	0.64	4.25	**EC5**	0.72	36.27	**SC4**	-0.38	6.02
6	**SC4**	-0.19	4.15	**SC2**	0.39	35.61	**EC5**	0.40	5.93
7	**SC2**	0.43	4.15	**EC4**	-0.16	35.34	**SC3**	-0.98	5.83
8	**SC3**	-0.75	4.03	**SC4**	-0.12	34.58	**SC2**	0.54	5.76
9	**EC4**	-0.36	3.97	**SC3**	-0.67	33.61	**EN1**	0.49	5.56
10	**SC1**	0.15	3.86	**SC1**	0.08	32.78	**SC1**	0.34	5.44
11	**EN1**	0.10	3.50	**EN1**	-0.06	27.42	**EC4**	-0.91	5.17
12	**EN2**	0.14	3.11	**EN2**	0.01	23.81	**EN2**	0.48	5.06
13	**EN3**	0.83	2.67	**EN3**	0.86	19.71	**EN3**	0.75	4.55

Table 7. Results of scenarios 4, 5, 6

	Scenario 4			**Scenario 5**			**Scenario 6**		
Rank		$r_i - c_j$	$r_i + c_j$		$r_i - c_j$	$r_i + c_j$		$r_i - c_j$	$r_i + c_j$
1	**EC1**	-0.41	5.29	**EC1**	-0.18	6.67	**EC1**	-0.30	59.03
2	**EC3**	0.14	4.65	**EC3**	0.07	5.83	**SC5**	0.11	51.69
3	**SC5**	0.22	4.63	**SC5**	0.27	5.79	**EC4**	0.24	51.35
4	**EC2**	-0.97	4.41	**EC2**	-1.02	5.51	**EC3**	-0.99	48.97
5	**EC5**	0.67	4.02	**SC4**	-0.29	5.12	**SC4**	0.60	45.02
6	**SC2**	0.42	3.93	**EC5**	0.52	5.12	**SC1**	-0.22	44.34
7	**SC4**	-0.16	3.90	**SC2**	0.48	4.98	**SC2**	0.45	43.91
8	**EC4**	-0.29	3.81	**SC3**	-0.87	4.97	**SC3**	-0.79	43.10
9	**SC3**	-0.72	3.79	**SC1**	0.25	4.68	**EC2**	-0.44	41.53
10	**SC1**	0.13	3.65	**EC4**	-0.64	4.59	**EC5**	0.18	41.02
11	**EN1**	0.04	3.22	**EN1**	0.31	4.57	**EN1**	0.16	38.16
12	**EN2**	0.10	2.84	**EN2**	0.32	4.12	**EN2**	0.20	34.03
13	**EN3**	0.84	2.41	**EN3**	0.79	3.64	**EN3**	0.81	29.56

The main results of the sensitivity analysis are as follows:

- In Scenario 1, the most important factor is EC1, followed by EC3 and SC5, while the least important factors are EN3, EN2, and EN1.
- In Scenario 2, the top three factors are EC1, EC3, and SC5, while the least important factors are EN3, EN2, and EN1.
- In Scenario 3, the most important factor is EC1, followed by EC3 and SC5, while the least important factors are EN3, EN2, and EN1.
- In Scenario 4, the top three factors are EC1, EC3, and SC5, while the least important factors are EN3, EN2, and EN1.
- In Scenario 5, the most important factor is EC1, followed by EC3 and SC5, while the least important factors are EN3, EN2, and EN1.

- In Scenario 6, the top three factors in the order of importance are EC1, SC5, and EC4, while the least important factors are EN3, EN2, and EN1.

Therefore, EC1, EC3, and SC5 are consistently ranked as the most important factors across different scenarios excluding Scenario 6. Also, EN3, EN2, and EN1 are consistently ranked as the least important factors. However, the ranking of the other factors varies depending on the scenario weights.

The cause groups for scenarios are given in Table 8.

Table 8. Cause group for each scenario

	EC1	EC2	EC3	EC4	EC5	EN1	EN2	EN3	SC1	SC2	SC3	SC4	SC5
Scenario 1			✓		✓	✓	✓	✓	✓	✓			✓
Scenario 2			✓		✓		✓	✓	✓	✓			✓
Scenario 3			✓		✓	✓	✓	✓	✓	✓			✓
Scenario 4			✓		✓	✓	✓	✓	✓	✓			✓
Scenario 5			✓		✓	✓	✓	✓	✓	✓			✓
Scenario 6			✓	✓	✓	✓	✓	✓		✓		✓	✓

The sensitivity analysis results reveal that the cause-and-effect groups are consistent across all six scenarios with minor differences. Traffic congestion (EC1), accessibility (EC2), and human health impact (SC3) are consistently in the effect group. Air pollution (EN3) emerges as the most significant causal factor, whereas other environmental factors noise pollution (EN2) and water pollution (EN1) lack comparable importance. This may suggest that PT is considered to have more negative effects on air than water and noise. Therefore, reducing air pollution (EN3) is the main challenge in PT sustainability transitions. Meanwhile, infrastructure (EC3), accident damage (EC5), affordability (SC2), and aesthetics (SC5) are also important causal factors for PT sustainability and require attention of decision-makers. The results show that there are no significant differences between the views of field and academic experts.

7. Conclusion

Sustainability within PT systems is a multidimensional issue that attracts both academic and practical interest. This study contributes to the field of sustainability analysis of PT in developing countries, through an application to the Twin Cities. Initially, a PT sustainability framework is constructed after a brief literature review. Then, a DEMATEL-based MCDM methodology is proposed, which quantifies the significance of each factor and lists the cause-and-effect groups among the factors. Then, the methodology is applied to a case study in Twin Cities. Finally, a sensitivity analysis is conducted by changing the weights of decision-makers' inputs. The outputs both provide the significance of each factor and cause and effect groups.

The findings underscore that traffic congestion emerging as the primary issue, closely followed by the infrastructure and aesthetics of PT. Particularly, while environmental concerns air, water and noise pollution are acknowledged, they are ranked lower in significance. This result indicates a gap in practice while prioritizing environmental sustainability within PT systems. Moreover, air pollution emerges as the most significant causal factor, highlighting the urgent need for corrective measures. Meanwhile, infrastructure enhancement, accident damage reduction, affordability, and aesthetics are other causal factors requiring attention. Furthermore, traffic congestion, accessibility, and human health impact appear consistently in the effect group highlighting that they are secondary. Their resolution depends on tackling the problems in the cause group. The sensitivity analysis shows that the output remains consistent across different scenarios, which reveals that academic and field experts have similar opinions on the factors.

The methodology developed and applied in this article is replicable in other cities located in developing countries. While the outcomes of this study are specific to the Twin Cities, they can be considered an example to decision-makers of similar residential settlements. Economic factors, such as infrastructure, traffic congestion, accessibility, etc. are the primary concerns for such regions, followed by social criteria such as aesthetics, affordability, and community cohesion. Finally, environmental concerns have the least prominence for them. Therefore, primary attention should be focused on improving the inadequate infrastructure and addressing PT-related problems and deficiencies. Meanwhile, social and environmental factors can simultaneously be integrated into the redesign and development processes of PT. Additionally, as the primary causal factor, air pollution must be tackled, which might be a result of poor urban planning and overpopulation. Furthermore, accident damage, affordability, aesthetics, and infrastructure emerge among the other causal factors and address the need for decision-makers' attention.

Future research directions may include taking inputs from other system shareholders such as the public, policymakers, and engineers to enable group decision making. Moreover, comparative analyses across cities can be conducted and each factor can be represented by multiple relevant sub-criteria. In addition, the prioritization of factors with DEMATEL can be integrated with MCDM methods such as AHP and TOPSIS to evaluate the sustainability performance of PT in developing countries. Furthermore, additional PT sustainability factors can be incorporated into the framework for a more comprehensive understanding. The main limitation of our study is the reliance of results on inputs from decision-makers and can be extended by increasing the number of decision-makers and their types.

Conflict of interest
The authors declare that there are no conflicts of interest associated with this article.

Contribution of researchers
Noman Shaukat led study design, model building, expert interviews, data collection, and analysis. Şenay Sadıç and Emre Demir conducted literature review, contributed ideas, refined methods, assisted with editing, and reviewed final draft.

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Appendix A

	EC1	EC2	EC3	EC4	EC5	EN1	EN2	EN3	SC1	SC2	SC3	SC4	SC5
EC1	0	3	3	1	3	3	3	5	1	3	2	1	3
EC2	3	0	2	3	3	1	1	2	3	3	1	2	3
EC3	2	2	0	3	3	1	0	1	2	2	1	2	3
EC4	2	2	2	0	1	0	1	0	3	2	0	2	3
EC5	3	0	2	1	0	2	1	1	0	1	3	1	1
EN1	3	1	2	0	1.6	0	0.4	0.4	1.2	0.8	2	1.2	1
EN2	2.8	1.2	1.4	0	1.6	0.4	0	0.4	0.2	1	1	1.2	1.4
EN3	1.6	0.2	0.4	0	1	0.6	0.2	0	0.2	1	1.2	0.4	1.2
SC1	1	2	2	2	1	0	0	0	0	3	1	3	2
SC2	1	2	2	2	1	0	0	1	2	0	1	2	2
SC3	2	2	1	0	3	3	3	3	3	1	0	1	1
SC4	0	1	3	3	1	1	2	1	2	2	1	0	3
SC5	0	3	3	1	3	3	3	5	1	3	2	1	3

Appendix B

	EC1	EC2	EC3	EC4	EC5	EN1	EN2	EN3	SC1	SC2	SC3	SC4	SC5
EC1	0	0.10	0.07	0.07	0.11	0.11	0.10	0.06	0.03	0.04	0.09	0.01	0.10
EC2	0.10	0	0.07	0.07	0.01	0.04	0.04	0.01	0.06	0.06	0.06	0.04	0.04
EC3	0.11	0.07	0	0.09	0.07	0.07	0.05	0.01	0.06	0.06	0.04	0.09	0.09
EC4	0.04	0.09	0.09	0	0.03	0.00	0.00	0.00	0.09	0.07	0.01	0.09	0.06
EC5	0.11	0.09	0.10	0.05	0	0.06	0.06	0.04	0.04	0.04	0.09	0.04	0.09
EN1	0.09	0.04	0.04	0.01	0.06	0	0.01	0.02	0.01	0.01	0.11	0.04	0.11
EN2	0.11	0.05	0.01	0.04	0.02	0.01	0	0.01	0.01	0.01	0.11	0.08	0.07
EN3	0.10	0.06	0.05	0.01	0.04	0.01	0.01	0	0.01	0.04	0.10	0.04	0.08
SC1	0.04	0.10	0.07	0.10	0.01	0.04	0.01	0.01	0	0.09	0.10	0.07	0.04
SC2	0.10	0.10	0.06	0.08	0.04	0.03	0.04	0.04	0.10	0	0.04	0.07	0.06
SC3	0.08	0.04	0.04	0.01	0.10	0.07	0.04	0.04	0.02	0.04	0	0.04	0.01
SC4	0.05	0.09	0.06	0.06	0.04	0.04	0.04	0.01	0.09	0.07	0.04	0	0.04
SC5	0.10	0.10	0.10	0.09	0.04	0.04	0.05	0.04	0.07	0.06	0.05	0.10	0