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A Spatial Approach to Balancing Demand and Supply in Combined Public Transit and Bike-Sharing Networks: A Case Application in Tehran

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Abstract

Combining public transportation (PT) with Bike-Sharing Systems (BSSs) offers a pathway toward the sustainable development of urban mobility. These systems can reduce fuel consumption, air pollution, and street congestion, especially during peak hours. Moreover, PT and BSS are frequently used by individuals without access to private vehicles, including low-income groups and students. Whereas increasing PT network infrastructure is constrained by issues such as high capital costs and limited street space (which inhibits mass transit options like BRT or trams), BSS can be used as an adaptable and affordable solution to fill these gaps. In particular, BSS can facilitate the "first-mile–last-mile" legs of PT journeys. However, many transit agencies still rely on traditional joint service planning and overlook BSS as a critical mode in integrated travel chains. This paper proposes that PT and BSS be considered as a unified network and introduces a framework to assess whether access to this integrated system is equitably distributed across urban areas. The framework estimates demand for travel using public mobility options and supply at the level of Traffic Analysis Zones (TAZs), treating PT and BSS as complementary modes. Spatial accessibility analysis is employed to examine connectivity using factors that affect access to both PT and BSS. The proposed approach is tested by taking Tehran as the focus of the case analysis. The results identify the most accessible areas and highlight those that require improved PT-BSS integration. These findings provide policy-relevant suggestions to promote equity and efficiency in urban transport planning. The outcomes reveal that central TAZs in Tehran receive the highest level of PT-BSS integration, while the western and southern TAZs are in urgent need of adjustment to ensure better distribution of integrated public transportation and bike-sharing services.

Keywords: public transportation; bike sharing system; equity; sustainability; supply–demand equilibrium; micromobility

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1. Introduction

Public transportation (PT) enables individuals to move around and reach jobs, local services, healthcare facilities, and leisure activities. A large number of individuals receiving public aid do not own personal vehicles and rely on public transit. This system provides an essential means of transportation for them and for all those without access to a private automobile.

In recent years, Bike-Sharing Systems (BSSs) have emerged as a useful mode for addressing the first and last mile of transit trips. Therefore, access to BSS in different parts

of the city should be considered when transportation planners assess traveler access and the demand for public mobility options.

PT contributes to approximately 20–30% of urban journey volumes in most metropolitan cities around the world, and BSS is increasingly being integrated to improve first- and last-mile connectivity [1]. By 2021, over 1600 cities worldwide were operating BSSs, serving more than 300 million users annually [2]. In Tehran, approximately 9.6 million daily trips are made using the public transport system, accounting for nearly half of all urban travel [3]. Nevertheless, Tehran's BSS is still in its early stages in terms of coverage, with only 30 operational stations. This has resulted in extreme spatial imbalances and underserved communities where BSS is not present [3]. Furthermore, in most cities, more than 40% of BSS trips have been found to originate from or terminate at PT stations, highlighting the benefits of integrated planning for system optimization and equity [4]. These statistics underline the critical need for tools to evaluate and optimize integrated PT–BSS in support of urban mobility, sustainability, and equitable access.

BSS riders often differ from regular PT users in several, often subtle, ways. They are generally younger, more likely to be male, and tend to have relatively higher incomes than typical PT passengers [5]. In addition, BSS trips are typically short-distance and used primarily for first- and last-mile connectivity, whereas PT trips tend to be longer and account for the majority of urban travel [2]. Keeping these distinctions in mind is important when examining demand, as BSS and PT are complementary systems that serve partially overlapping user groups and travel purposes.

Urban areas are centers of social and economic activity. The expansion of cities increases the complexity and diversity of services. Transportation enables people to engage in various activities such as employment, shopping, and recreation, and to access healthcare and educational services [6]. The primary goal of transportation is to ensure accessibility and to establish effective connections between origins and destinations [7,8]. Land-use-related factors that contribute to trip generation and increased transport demand include housing concentration (typically indicated by population density), the spatial distribution of land uses, and the presence of major urban destinations [9]. Several elements influence the balance between car use and public transport, including the city's characteristics, the extent of urban development, policy-driven changes in growth patterns, the current quality of transit services, and plans for future improvement [10]. Often, relying on a single mode of public transportation is not sufficient to fully meet passengers' needs, prompting many to prefer private vehicles or taxis to overcome limited accessibility. Nevertheless, incorporating bicycles as a first- or last-mile option can significantly reduce the total travel time associated with public transport journeys [11].

Over recent decades, several industrialized countries have adopted the integration of public transport and cycling as a means to address one of the key shortcomings of conventional public transport systems. Coupling bus services with bicycle travel promotes reduced dependence on private cars and supports the development of more sustainable transport systems.

Although the benefits of integrating PT and BSS are well recognized, many cities face challenges in coordinating them effectively. Current systems are often characterized by poorly planned BSS station locations around key PT hubs, which undermines first- and last-mile connectivity. In addition, spatial mismatches between supply and demand frequently occur—where high-demand areas lack sufficient bikes or PT capacity, while low-demand areas are overserved [2,12]. These issues limit the effectiveness of integration and may reinforce urban mobility inequities [4,13].

Recent research has primarily focused on operational efficiency, mode shift impacts, and the governance of integrated PT–BSSs [14,15]. Nonetheless, there is still a need to

develop quantitative models that assess the spatial supply–demand balance of integrated PT–BSSs at the TAZ level. Without such frameworks, planners lack evidence-based tools to identify underserved areas and to optimize system planning for greater equity and sustainability. Therefore, the aim of this study is to develop and apply a spatial tool that evaluates the supply–demand balance in integrated PT–BSS networks. The tool combines accessibility and demand assessments at the TAZ scale to identify mismatched regions and to offer practical recommendations for planners. The specific research questions addressed are as follows:

- How can GIS-based spatial analysis techniques be applied to quantify demand and accessibility for integrated PT–BSSs across urban TAZs?
- Which areas in the study context show the highest imbalances between demand and supply of PT–BSS services?
- How can the results of this spatial accessibility analysis inform planning interventions to enhance equity and efficiency in multimodal public transportation systems?

This study bridges the knowledge gap by establishing a holistic spatial evaluation framework for integrated PT–BSSs.

The proposed model is applied to the city of Tehran as a case study, drawing practical lessons relevant to policy-making and transport planning. It aims to bridge the research gap regarding the lack of numerical methods for assessing the supply–demand balance in integrated multimodal PT networks.

The objectives of this research are outlined below:

1. To apply spatial accessibility analysis methods based on GIS buffer zones and supply–demand metrics to evaluate the performance and equity of integrated PT and BSS.
2. To conduct a zone-level spatial assessment in the case of Tehran, analyzing demand, accessibility, and supply–demand balance across TAZs.
3. To identify areas with significant mismatches between service provision and local demand, highlighting zones that are under-supplied or over-supplied.
4. To support data-driven and equitable transportation planning by providing spatial insights and actionable recommendations for optimizing integrated PT–BSS networks.

The remaining sections of this paper are organized as follows:

Section 2 presents a review of the relevant literature, including the importance of supply-demand balance, methods for evaluating PT and BSS, and recent studies that integrate these two systems. Section 3 provides the proposed methodology, such as demand, supply, and equilibrium measurement criteria in integrated PT–BSSs. Section 4 provides an application of the case study in Tehran, including data, analysis, and results of applying the proposed criteria. Section 5 concludes the paper by summarizing the major findings, offering policy recommendations, identifying limitations, and suggesting directions for future research.

2. Literature Review

During the last few decades, many studies have been conducted on PT. Several mathematical functions and algorithmic techniques have been employed by researchers to solve problems related to PT networks and to determine the most efficient routes based on bus frequencies, stops, locations, and costs. Additionally, micromobility options offer practical solutions for short-distance travel and are especially effective in addressing the last-leg challenges of PT. When used as a complementary mode to support the initial and final segments of transit journeys, micromobility can contribute to increased bus

usage. It may also replace short transit rides or even generate new trips motivated by leisure purposes.

2.1. Importance of Balancing Supply and Demand

Public transport is often marketed as integral to overall city mobility strategies for relieving traffic congestion and reducing emissions from motorized transport [16]. Additionally, large public transport investments are broadly welcomed due to their ability (during both construction and operation) to stimulate local and regional economic growth [17]. In the United States, aside from the annual USD 38 billion allocated for PT operations, recent public transport infrastructure expenditures have exceeded USD 18 billion annually [18]. Such investments should be evaluated based on their net impact on societal well-being, taking into account both initial capital costs and ongoing maintenance and operating expenses [19]. Although the broader debate around funding mechanisms for transport and its role in American city mobility has been explored by researchers such as [20,21], the specific role of PT in mitigating traffic congestion remains a key part of this evaluation. However, researchers have yet to reach a conclusive empirical determination regarding the magnitude of PT's impact. When it comes to investment decisions in PT, evaluating demand–supply equilibrium is essential for designing new routes, planning system development, and allocating budgets effectively.

Concerning BSS as a supplemental mode, the supply–demand equilibrium plays a significant role in determining the performance of a bike-sharing system. A proper balance increases bicycle usage and facilitates system expansion. In contrast, imbalances between supply and demand can create difficulties in efficiently reallocating bikes [22].

Supply–demand equilibrium applies to both PT and BSS. Low supply relative to demand results in overcrowding, lower service quality, and potential ridership loss due to discomfort or long waiting times in PT. On the other hand, excess supply compared to demand leads to underutilized assets and economic inefficiencies. In the case of BSS, imbalances are experienced as bike shortages at high-demand stations and bike surpluses at low-demand stations, resulting in user dissatisfaction and high rebalancing costs. When these two systems are integrated, maintaining supply–demand balance becomes even more critical. For instance, even if PT supply is sufficient, a lack of bikes at nearby BSS stations (or vice versa) can reduce the effectiveness of the integrated travel chain. This discourages multimodal trips and lowers overall system efficiency. Therefore, achieving a balanced supply and demand in both PT and BSS is essential for ensuring seamless intermodal connectivity, maximizing resource utilization, enhancing user satisfaction, and advancing broader goals of sustainable and equitable urban mobility.

2.2. Importance of Considering BSS Integrated with PT

BSS can serve as a practical solution for covering the first or last segments of a journey linked to PT. In terms of cost, renting a bicycle is typically less expensive than hiring a car. Studies suggest that BSS has more effectively replaced walking trips than car trips [5]. The5 interaction between BSS and PT can be characterized by BSS facilitating the often-challenging first-mile (access) and last-mile (egress) segments of transit travel, rather than competing with them. The maximum distance people are typically willing to walk to a station is around 400 m for both access and egress [23].

Research shows that individuals are more willing to walk longer distances to reach high-performance transit modes such as subways and trains, compared to lower-capacity modes like buses and trams, as observed in the Oslo area [24]. In any case, integrating BSS as an access–egress mode for PT can be beneficial to both systems [14]. BSS docks located near train stations tend to experience higher ridership [13]. For example, bike-sharing has

reportedly increased rail usage by 10% in Montreal [25]. Survey-based studies have also shown that people actively combine BSS with PT. In Beijing and Hangzhou, more than half of bike-sharing users reported using both modes together [2].

Based on previous studies on the integration of PT and BSS, these two systems work more effectively when considered together, and they should not be analyzed separately in cities where both systems are present. PT and BSS can influence the demand for one another; therefore, when analyzing demand and supply for PT in a city, BSS should also be taken into account.

2.3. Evaluating the Spatial Distribution of Demand

In measuring the demand for access to public mobility modes, including integrated PT and BSS, various key parameters have been widely applied in different studies. These include the number of low-income earners, households without a car, students, and the total population in each TAZ [26]. Generally, these groups are more likely to rely on public mobility options for their daily travel needs [27]. Selecting the appropriate parameters is crucial for accurately assessing the spatial demand for integrated PT and BSS, as these population segments represent a significant potential user base for such networks. Data were aggregated at the TAZ level because relevant variables—such as population figures, vehicle ownership rates, household income, and student numbers—were available at that spatial resolution.

2.4. Evaluating Supply of PT

Transportation supply is frequently associated with concepts like accessibility and mobility. In practice, it is often assessed based on how effectively a user can navigate the city or the range of destinations reachable through the transit network. One of the most common mobility-based metrics (due to its simplicity) is the amount of service operating through a station or stop [28,29]. On a larger scale, one of the most frequently employed indicators of transportation supply related to mobility is the total vehicle miles traveled within a regional area [30]. Although such indicators offer a straightforward numerical assessment of transit availability at a given stop or area, they often fail to capture more complex and critical factors related to service quality.

Accessibility metrics typically emphasize either the distance between residences and nearby transit stations [31], or the time it takes to commute from home to the workplace using public transportation [32]. These indicators are commonly calculated using GIS to estimate the travel time required for specific trips by each transportation mode [33]. Numerous equations have been proposed in past studies to evaluate the supply of PT, each suited to specific types of research. Therefore, the appropriate method should be selected based on the available data and the study objectives [33]. This study introduces a set of indicators grounded in graph theory to define connectivity across various types of transit services. Using connectivity as a metric allows for the evaluation and quantification of service levels in multimodal networks, reflects layered transit capacity for planning purposes, assesses how effectively nodes and stops are prioritized, and provides an intuitive tool for identifying areas with optimal connectivity when transit is the chosen mode of travel. The proposed method is explained in detail in Section 3.2.

2.5. Evaluating Supply of BSS

The efficiency of BSS stations depends on several parameters [34]:

The distance to nearby PT stations affects the efficiency of BSS. Additionally, offering access to both services through a smart card at an affordable rate may encourage greater use of the Bike-Sharing System [2,35–37]. The number of available bikes at a station is another important parameter [38]. Street connectivity reflects the quality of infrastructure

and the level of traffic safety in the vicinity of a Bike-Sharing Station [39]. Depending on the context, this factor may or may not be considered; it is typically measured by counting intersections and calculating road network density in the area. Slope presents a significant barrier to cycling and has a strong influence on bicycle usage rates [40]. It can be evaluated by analyzing the gradient levels of specific streets and calculating the proportion of streets within particular slope ranges across the city and surrounding service area [41].

When considering BSS as an integrated system with PT, the most important parameter is the presence of a PT station near the BSS station, enabling its use for the first and last mile of a bus rider's journey.

2.6. Prior Studies on PT-BSS Integration

Several studies have explored the integration of PT and BSS. For example, Ji et al. [42] analyzed metro–bikeshare transfers using geographically weighted Poisson regression to identify spatial variations in transfer patterns. Martin and Shaheen [25] studied the impact of bike-sharing on PT modal shift and showed that BSS boosts rail usage, although with varying effects depending on the city. Goodman and Cheshire [13] evaluated cycling inequities in London and found that inequities remained prevalent despite increased access. Fishman et al. [2] conducted a global review of BSS and PT integration, highlighting benefits but lacking quantitative models for assessing integrated accessibility and demand. Liu et al. [4] examined multimodal travel fairness and efficiency, but did not focus on modeling supply–demand balance. Ye et al. [15] provided a thorough investigation of bike-sharing coopetition dynamics, but their focus remained on governance and operational issues, with little attention to spatial access inequality. Collectively, these studies demonstrate the potential benefits of integrating PT and BSS for boosting ridership and promoting sustainable travel. Nonetheless, key challenges remain. Most existing research focuses on modal shifts or operational indicators, while few address spatial supply–demand balance at the zonal level. Little work has been carried out to develop comprehensive frameworks that assess both equity and accessibility in integrated systems. Currently, there is a lack of methods capable of identifying underserved regions to support targeted planning interventions.

Table 1 outlines the current body of research, indicating that while previous studies have examined operational indicators, modal shifts, or equity-related aspects, none have developed a comprehensive spatial equilibrium model for integrated PT–BSSs—something this study aims to accomplish.

Table 1. Summary of authors' contributions, methods, findings, and gaps in PT-BSS integration Studies.

Author(s) and Year	Focus/Objective	Methods/Approach	Key Findings	Limitations/Gaps
Ji et al. (2018) [14]	Metro–bikeshare transfer patterns	Geographically weighted Poisson regression	Identified spatial variations in metro–bikeshare transfers	Did not assess supply–demand balance or equity implications
Martin & Shaheen (2014) [25]	Impact of bikeshare on PT modal shift	Comparative analysis (2 US cities)	BSS increases rail usage by ~10%	Focused on modal shift; no integrated accessibility-demand framework
Goodman & Cheshire (2014) [13]	Equity of London bikeshare system	Spatial GIS analysis	Found persistent equity gaps despite expanded access	No integration with PT; lacked supply–demand evaluation
Fishman et al. (2013) [2]	Global BSS literature synthesis	Systematic literature review	Enumerates explicit BSS advantages on urban mobility	Did not present quantitative appraisal models for incorporation

Table 1. *Cont.*

Author(s) and Year	Focus/Objective	Methods/Approach	Key Findings	Limitations/Gaps
Liu et al. (2024) [4]	PT-BSS travel efficiency and fairness	Multiscale accessibility analysis	Highlighted inequities in integrated PT-BSS	Did not model spatial supply–demand balance
Ye et al. (2024) [15]	Coopetition dynamics in bike-sharing	Systematic literature review	Identified governance and operational challenges	Did not examine spatial equity or supply–demand balance
Zhu et al. (2024) [43]	Driving factors of BSS commuting demand	Spatial statistical analysis	Found that PT proximity is crucial for BSS usage	Did not establish a full evaluation system
Zhang et al. (2024) [12]	Multimodal data-based congestion prediction	Spatial–temporal graph transformer networks	Demonstrated AI-based congestion predictions	Did not develop systems that integrate supply–demand balance
Lopes et al. (2025) [44]	Inclusion of BSS-PT systems and accessibility equity	Accessibility equity assessment	Integrated systems improve access for low-income consumers	Did not simulate zonal supply–demand balance
Wang et al. (2025) [45]	Roadmaps for public transport development in China	Strategic policy analysis	Advocated PT integration with micromobility for sustainability	Did not suggest spatial equilibrium appraisal frameworks
This study	Estimate supply–demand balance for integrated PT-BSS networks	Spatial model that connects accessibility, demand, and balance indices at TAZ level and lists underserved regions	Identifies underserved zones; provides actionable planning insights	Drives practical planning recommendations holistically closes the gap by developing an integrated, quantitative, network, and equilibrium evaluation model of PT-BSS

2.7. Research Gap

Recent research has continued to focus on integrating BSS and PT to improve urban mobility, equity, and operational efficiency. For example, Zhao et al. [42] evaluated the impact of accurate trip demand forecasting on BSS operational efficiency across various urban structures, concluding that more precise forecasts significantly reduce rebalancing costs and enhance system utilization. Liu et al. [4] examined multimodal travel efficiency and fairness by integrating PT and BSS, highlighting accessibility inequities and proposing planning frameworks to improve service allocation. Ye et al. [15], in a systemic review, presented strategic roadmaps for the development of public transport in China, recommending greater integration with micromobility modes such as BSS to mitigate urban congestion and support sustainability goals. Wang et al. [45] analyzed factors influencing bike-sharing commuting demand and found that spatial distribution and proximity to PT play key roles in shaping usage patterns. Similarly, Zhu et al. [43] investigated commuting demand for bike-sharing and confirmed the importance of spatial distribution and PT proximity. In another study, Zhang et al. [12] applied spatial–temporal graph transformer networks to predict urban congestion using multimodal transportation data, demonstrating the growing role of AI in optimizing mobility systems. Equity remains a central concern. Su et al. [46], for example, compared shared e-scooters and docked bikeshare systems, revealing differences in their spatial equity outcomes and implications for mobility justice. Lopes et al. [44] assessed the effects of bike-sharing and transit connectivity on accessibility equity, concluding that integrated systems significantly improve access opportunities for low-income and carless populations. Lastly, Zhao et al. [42] proposed location-routing optimization models to manage supply and demand uncertainties in BSS fleet operations within dynamic urban contexts. Despite these advances, few recent studies have developed a fully integrated spatial model that balances supply and demand for both PT and BSS across all TAZs. Most continue to treat PT and BSS separately or focus exclusively on either operational performance or fairness, without considering both within a unified spatial

framework. This study addresses that gap by developing and applying a comprehensive spatial model that evaluates the balance between accessibility and demand for PT and BSS as components of an integrated public mobility network.

3. Methodology

In this study, TAZs are selected as the spatial units for evaluating the supply and demand of PT and BSS across the city. Figure 1 illustrates the methodology, showing a flowchart of the proposed analytical framework.

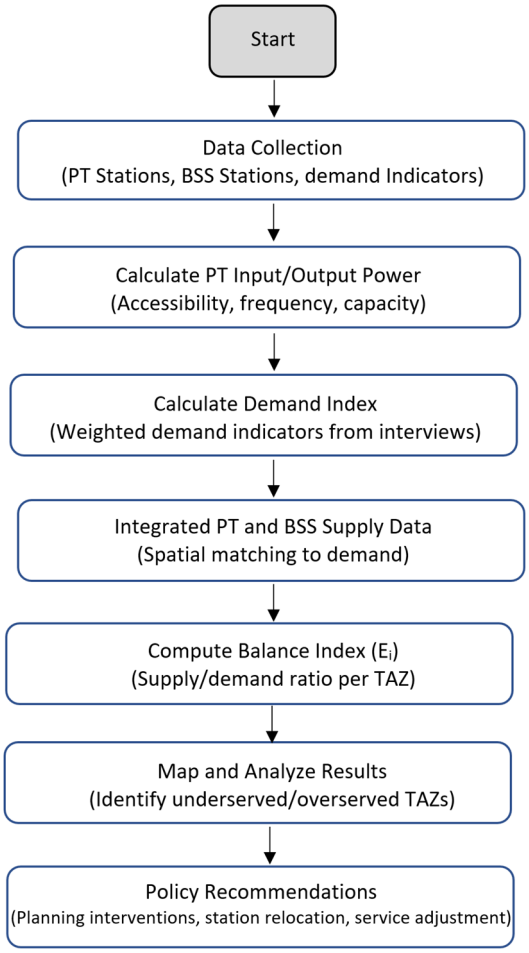


Figure 1. Flowchart of the proposed integrated PT-BSS supply–demand evaluation framework.

Framework Definition

The framework consists of the following key components. First, PT accessibility is systematically calculated using input–output power metrics. Then, BSS accessibility is assessed based on spatial proximity. Next, weighted demographic demand is estimated using census data and expert interviews. Finally, the spatial balance index (E_i) is calculated to identify underserved and overserved areas. This structured framework combines spatial analysis, accessibility modeling, and equity-based prioritization to support strategic planning for multimodal transport systems.

3.1. Evaluating the Demand for Integrated PT-BSS

Demand for PT can be estimated by identifying factors that correlate with the use of the public transport system. The number of low-income individuals, the total population [27], and the number of carless people in each zone [47] are effective indicators for estimating zonal demand for public transportation. Generally, as the population of a zone increases,

so does the demand for PT. Additionally, low-income individuals are often the primary users of public transport [13].

3.2. Evaluating Access of Each TAZ to Public Mobility Options Trips

To evaluate the accessibility of TAZs to public mobility options, access to public transport (including bus, metro, monorail, and tramway) as well as access to BSS should be calculated. The methodology for this calculation is explained in Sections 3.2.1 and 3.2.2.

3.2.1. Evaluating Access to PT

All PT stations serve as connection nodes between the transit network and passengers. Based on this, the concepts of input and output power can be introduced for each station and the transit routes serving it. The connectivity power of a station reflects the amount of transit service provided there, taking into account factors such as the number of vehicles, service frequency, line capacity, and average running speed. The input power $P^i_{l.n}$ and output power $P^o_{l.n}$ or station n, corresponding to its connection with line L, are calculated using Equations (1) and (2), respectively [33].

$$P^i_{l.n} = \alpha * C_l * f_l * H_l * D^i_{l.n} * V_l \quad (1)$$

$$P^o_{l.n} = \alpha * C_l * f_l * H_l * D^o_{l.n} * V_l \quad (2)$$

In these formulas, C_l denotes the capacity of each vehicle, f_l refers to the service frequency, H_l indicates the total service hours within a 24 h period, V_l represents the operating speed of the line, $D^o_{l.n}$ denotes the distance to the last station from the first station of the line and $D^i_{l.n}$ denotes the distance to the last station from station i of the line.

The coefficient α has been included for standardizing and non-dimensionalizing the power in the equation. It is defined following the formulation presented in [33], and is used to normalize and non-dimensionalize the power of public transit stations. It is calculated as $\alpha = 1/(C*\mathrm{f}*\mathrm{H}*D*V)$. where C is the average capacity of vehicles (passengers), f is the frequency of departures per hour, H is the number of operating hours per day, V is the average speed and D is the service radius of the station. The coefficient accounts for the spatial coverage of each station, making the normalized power values more representative for spatial comparison. The connectivity power of every station for each $P^t_{l.n}$ line is equal to its average input and output power.

For each station, both input and output power values are computed, and their average is taken as the total power generated by line L at station I. The overall transit power available to the public at each station is obtained by summing the contributions of all lines serving that station.

$$P^t_{l.n} = \left(P^i_{l.n} + P^o_{l.n}\right)/2 \quad (3)$$

The total power of each station is calculated by adding up the power contributions of all lines that serve it.

$$P^t_n = \sum_{l.n \in l} P^t_{l.n} \quad (4)$$

3.2.2. Evaluating Access to Integrated BSS to PT

Accessibility to integrated BSS and PT across different TAZs can be evaluated by assessing the connectivity strength of BSS stations to PT stations. For each spatial parameter, the Zonal Statistics function in ArcGIS was used to compute the average value within a specified buffer around each station. A 400 m buffer was applied for sociodemographic variables, representing the standard walking distance people are typically willing to travel to access BSS. Since the average walking distance to reach transit stations is approximately

400 m [48], it was assessed whether a PT station was located within this range. Based on these parameters, a reliable evaluation of each TAZ's access to integrated BSS–PT service can be conducted. The 400 m threshold was chosen based on widely cited studies identifying it as the longest convenient walking distance for first- and last-mile BSS use [49], and to align with common accessibility standards used in transportation system planning.

Managing Missing Frequency Data: A total of 3.2% of frequency values in the dataset were missing, mostly from low-frequency feeder lines. The missing values were filled in with the mean frequency from all the valid values on all the lines. The reason for choosing this method is that there is a relatively small percentage of missing data and the frequency variable has a distribution that is almost normal. Sensitivity analysis showed that the imputation affected the accessibility index (A_i) values by less than 2.5%. This means that the overall model results were only slightly affected.

3.3. Method of Integrating Supply of PT and BSS in TAZs

After evaluating the accessibility of different TAZs to PT and BSS separately, the accessibility of TAZs to the integrated PT–BSS system should be calculated. However, these two types of accessibility must be standardized before combining them. To achieve this, PT accessibility in each TAZ is categorized on a scale from 1 to 5. Similarly, BSS accessibility is also assessed and classified into one of five levels. These two standardized values are then summed to estimate each TAZ's overall accessibility to the integrated PT–BSS system.

To explain how the accessibility of TAZs to BSS and PT was scored from 1 to 5, the raw accessibility values were first normalized to a 0–100 scale. Then, these values were categorized into five accessibility grades using the equal interval method, in which the value range is divided into five equal-width classes. Each grade represents a fixed portion of the total score range. Level 1 indicates the lowest accessibility, while Level 5 indicates the highest.

The final accessibility index (A_i) for each TAZ is derived by integrating two core components: the PT power and the connectivity of BSS stations to nearby PT nodes within a walkable distance. Each component is first normalized and classified on a five-level scale. This integration allows A_i to reflect both the service intensity of PT and the availability of first-last-mile connections through BSS. Therefore, areas with both high PT service levels and strong BSS connectivity achieve higher A_i values, while underserved zones in either mode score lower. This formulation ensures that A_i captures not only proximity but also multimodal accessibility strength, supporting a more equitable and realistic assessment of transport service coverage.

3.4. Assessment Balance in Supply and Demand (E_i)

The imbalance between demand and supply in each TAZ is calculated using a normalized ratio, adapted from the spatial equity method introduced by Akbarzadeh and Mortazavi (2017) [48]. The equilibrium index (E_i) compares normalized demand and accessibility values to identify under-served or over-served areas.

$$E_i = \left(\frac{D_i}{D_{max}}\right) / \left(\frac{A_i}{A_{max}}\right) \quad (5)$$

where

E_i = balance index for TAZ_i;
D_i = demand for PT–BSS in TAZ_i (see Section 3.1);
D_{max} = maximum value of demand across all TAZs;
A_i = access index of TAZ_i (see Sections 3.2 and 3.3);
A_{max} = maximum access index across all TAZs.

This formula reflects the same logic as used in the study of public transit equity in Isfahan [48].

Interpretation of E_i levels: In planning and interpreting, the E_i values were categorized into three balance levels: $E_i < 0.8$ (signals that the demand surpasses the accessible supply). Such areas need immediate responses, for example, higher frequency of PT service, higher number of BSS stations, or improved connectivity. $0.8 \leq E_i \leq 1.2$ (Balanced): This indicates that supply is reasonably matched to demand, suggesting adequate service provision without immediate need for major investment. $E_i > 1.2$ (Over-supplied): This indicates that supply significantly exceeds demand, implying underutilized resources where efficiency improvements or resource reallocation may be considered.

This categorization enables planners to prioritize equity-driven interventions and identify areas where service delivery may require redesign for greater efficiency and fairness. The ±20% buffer range used here aligns with accepted deviation margins used in public transit performance analyses (Mishra et al., 2012) [33] and spatial equity studies (Delbosc & Currie, 2011) [49].

This categorization enables planners to systematically prioritize interventions. Under-supplied areas can be targeted for infrastructure expansion or service enhancements, while over-supplied areas may benefit from optimization efforts aimed at improving cost-effectiveness and overall system sustainability.

3.5. Analysis of Outcomes

After calculating the balance index (E_i) for all TAZs, the analysis of the resulting values revealed spatial patterns of supply–demand mismatch. TAZs were graphically represented based on their balance values, allowing for the visual identification of underserved and overserved areas. Application for decision-making: The results of the balance analysis have significant implications for transportation planners and decision-makers. For instance, infrastructure planning can target underserved areas for additional PT services, increased frequencies, or new BSS station installations. In cases of oversupply, resource optimization can be pursued by reducing redundant PT capacity or reallocating BSS docks. In terms of equity considerations, mapping balance levels highlights spatial disparities in the provision of integrated PT–BSS services, supporting more equitable resource allocation. For strategic integration planning, the outcomes help guide first- and last-mile connectivity improvements, encouraging system efficiency and environmentally friendly shifts away from car use.

Overall, the framework and its results provide evidence-based guidance to enhance the effectiveness, efficiency, and equity of integrated PT and bike-sharing systems in cities.

4. Case Study

In this study, Tehran was selected to analyze both the service provision and the distribution balance in its PT system. Tehran experiences a daily total of approximately 19.3 million trips, with nearly half attributed to public transportation services, according to official statistics [50]. To conduct the analysis, data on the BRT system—which consists of 235 active stations and ten lines (as of January 2021)—along with data from Tehran's metro network—which has 115 stations and seven lines—were provided by the Tehran Deputy for Traffic and Transportation. Data on BRT and metro infrastructure correspond to January 2021, which was the latest verified dataset at the time of model implementation. Tehran also has a Bike-Sharing System that began operating in 2018, with 30 stations in service as of January 2021.

Data Sources and Description

This study utilized a number of datasets to analyze the demand, supply, and balance of the integrated PT system and BSS in Tehran. PT station data—including the location, type (metro or BRT), service frequency, and capacity—were obtained from the Tehran Traffic and Transportation Organization. BSS station data—including station locations and dock capacities—were obtained from the Tehran Bike-Sharing Operator Database.

Socioeconomic data, such as the number of carless households, low-income households, students, and population aged 16 years and above, were taken from the 2021 Population and Housing Census and were aggregated to TAZs. Spatial boundary shapefiles of TAZs were downloaded from the Tehran Urban Planning and Research Center to define the analysis units. The TAZs used in this study correspond to official census tracts in Tehran, aligning with neighborhood boundaries and commonly adopted spatial units in transport planning analyses.

Regarding PT, data on speeds, service frequencies, fleet size, and daily operating hours were obtained from Tehran's subway and bus companies. All missing values in the frequency data were imputed by applying the average value of the relevant parameter across all lines. An overview of the data sources is provided in Table 2.

Table 2. Required data for computing the connectivity power of PT stations.

Parameter	Unit	Descriptive Statistics (BRT)		Descriptive Statistics (Metro)	
		Min	Max	Min	Max
Frequency	Number/h	6	24	3	10
Speed	Km/h	17	50	130	140
Number of daily working hours	hour	15.5	16.5	16	17
Fleet's capacity	person	34	40	1423	1423
Distance to the last station	km	0.93	37.5	0.31	33
Distance to the next station	km	0.54	1.75	0.17	1.3

4.1. Access of Tehran's TAZs to PT

To calculate the accessibility of different TAZs to PT, Equations (1) and (2) were used. The input and output power of PT stations in Tehran were computed using the proposed methodology.

PT service levels in each TAZ were determined by aggregating the connectivity power of all stations located within that TAZ. First, data on BRT and metro stations in Tehran (including speeds, service frequencies, daily operating hours, and the size of the transit fleet for both bus and metro lines) were collected. The objective was to calculate the input and output power of each station. These calculations were performed for all operational metro and BRT stations in the city. The current distribution of PT stations is illustrated in Figure 2.

The station powers within each TAZ were aggregated to determine its PT power. Figure 3 illustrates the distribution of PT power across TAZs in Tehran.

TAZs are classified into four distinct groups based on their PT power. A power status in the first quartile is defined as the worst, and a power status in the fourth quartile is defined as the best.

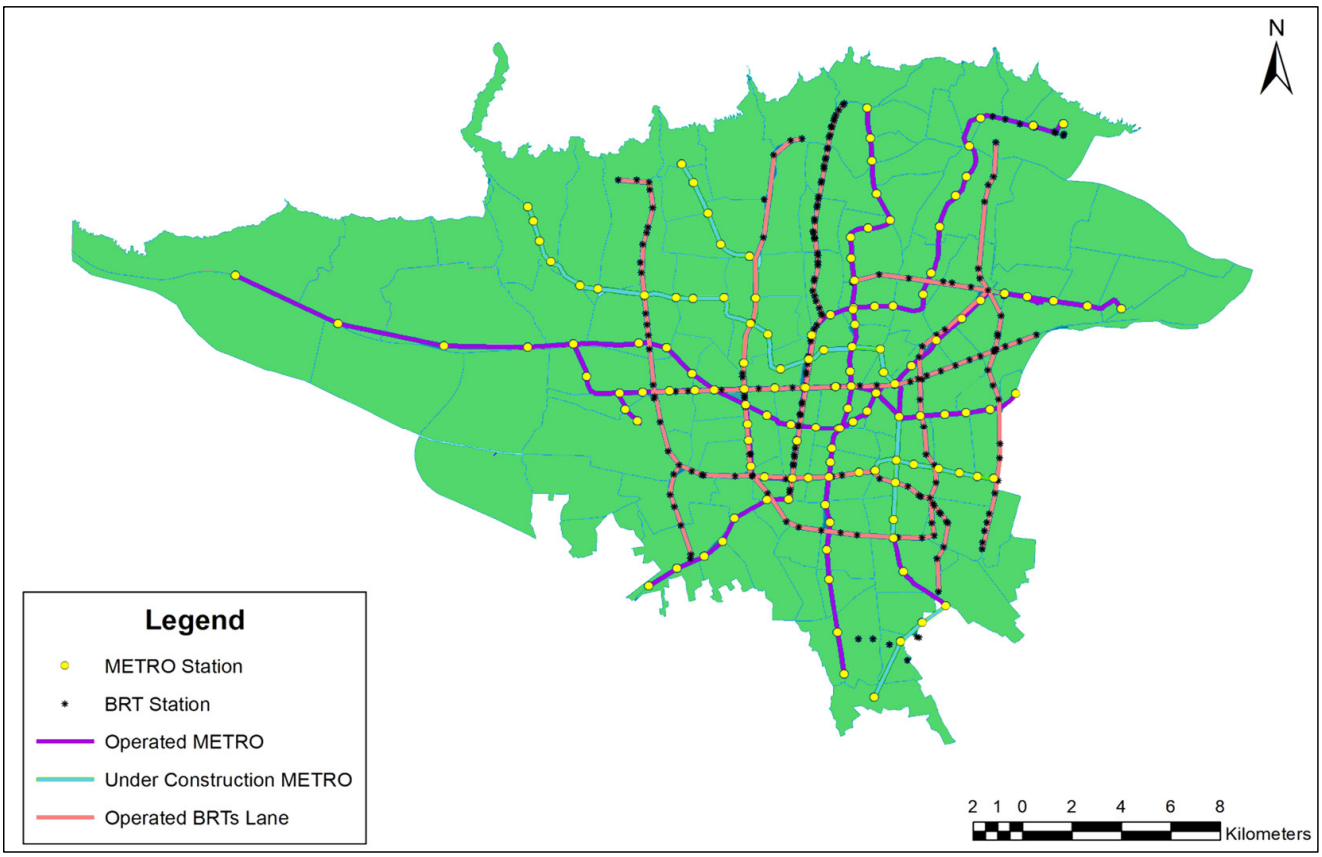


Figure 2. Tehran PT network overview.

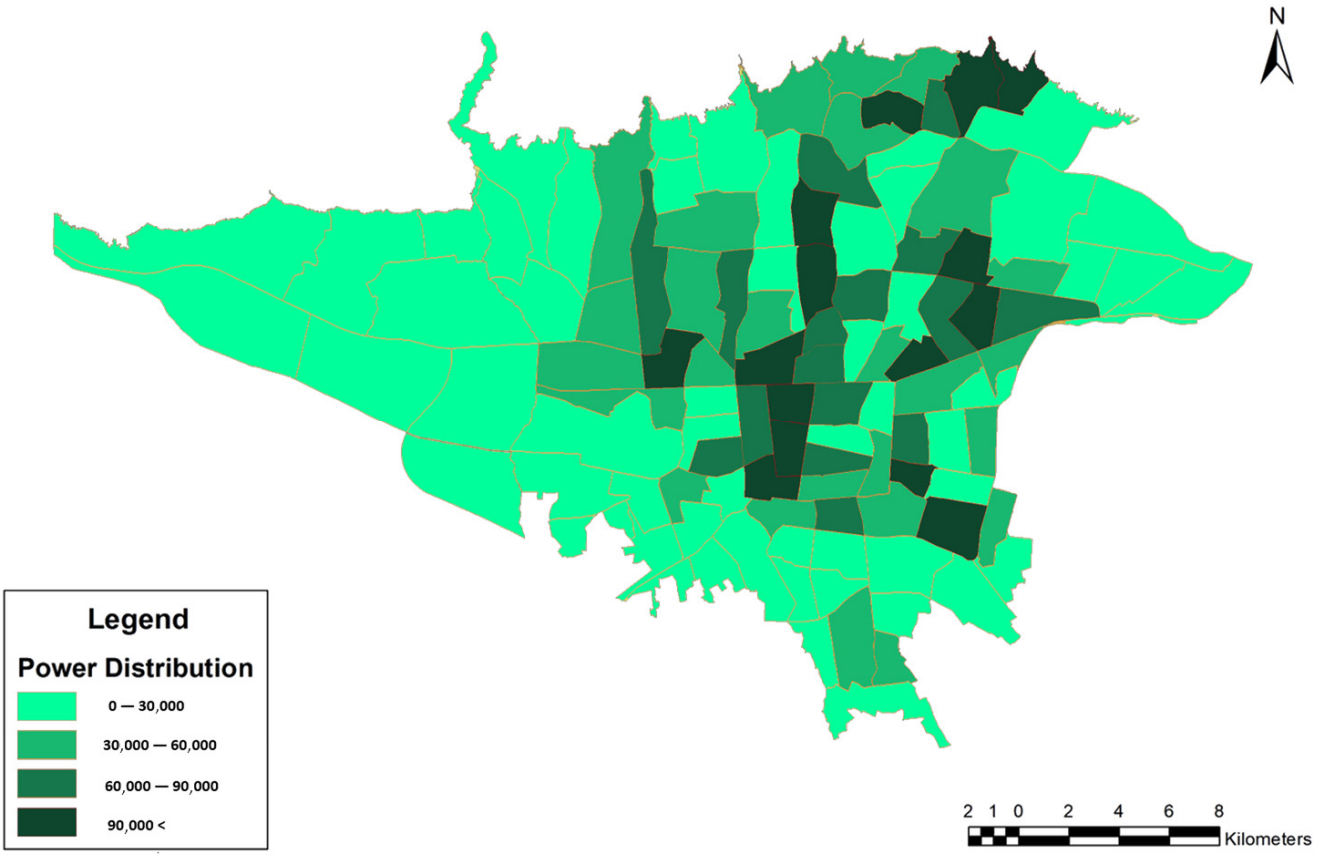


Figure 3. PT power distribution in different TAZs in the current situation.

4.2. Access of Tehran's TAZs to BSS

There are 30 BSS stations in Tehran [51], and their locations are shown in Figure 4. To evaluate the accessibility of different TAZs to the BSS integrated with PT, the following method was used: BSS stations located within a 400 m radius of a PT station were identified and assessed. If a region did not contain any BSS station, its accessibility to BSS was considered zero.

For regions with more than one station, the overall accessibility to the bike-sharing system was determined by summing the accessibility scores of all stations located within the region. Similarly, for PT (as described in Section 3.2.1), the overall accessibility of each TAZ was calculated by aggregating the accessibility powers of all transit stations located within its boundaries, representing the strength of the public transit system in that area. The accessibility of these BSS stations is illustrated in Figure 5.

4.3. Access of Tehran's TAZs to the Integrated System of PT and BSS

After calculating the individual supply levels of PT and BSS across the TAZs of Tehran, the combined supply of the integrated PT–BSS system was determined using the method outlined in Section 3.3. The level of access to this integrated system was then evaluated for each TAZ, and the results are shown in Figure 6. According to the map legend, the first quartile represents areas with the lowest access or supply, while the fourth quartile indicates areas with the highest.

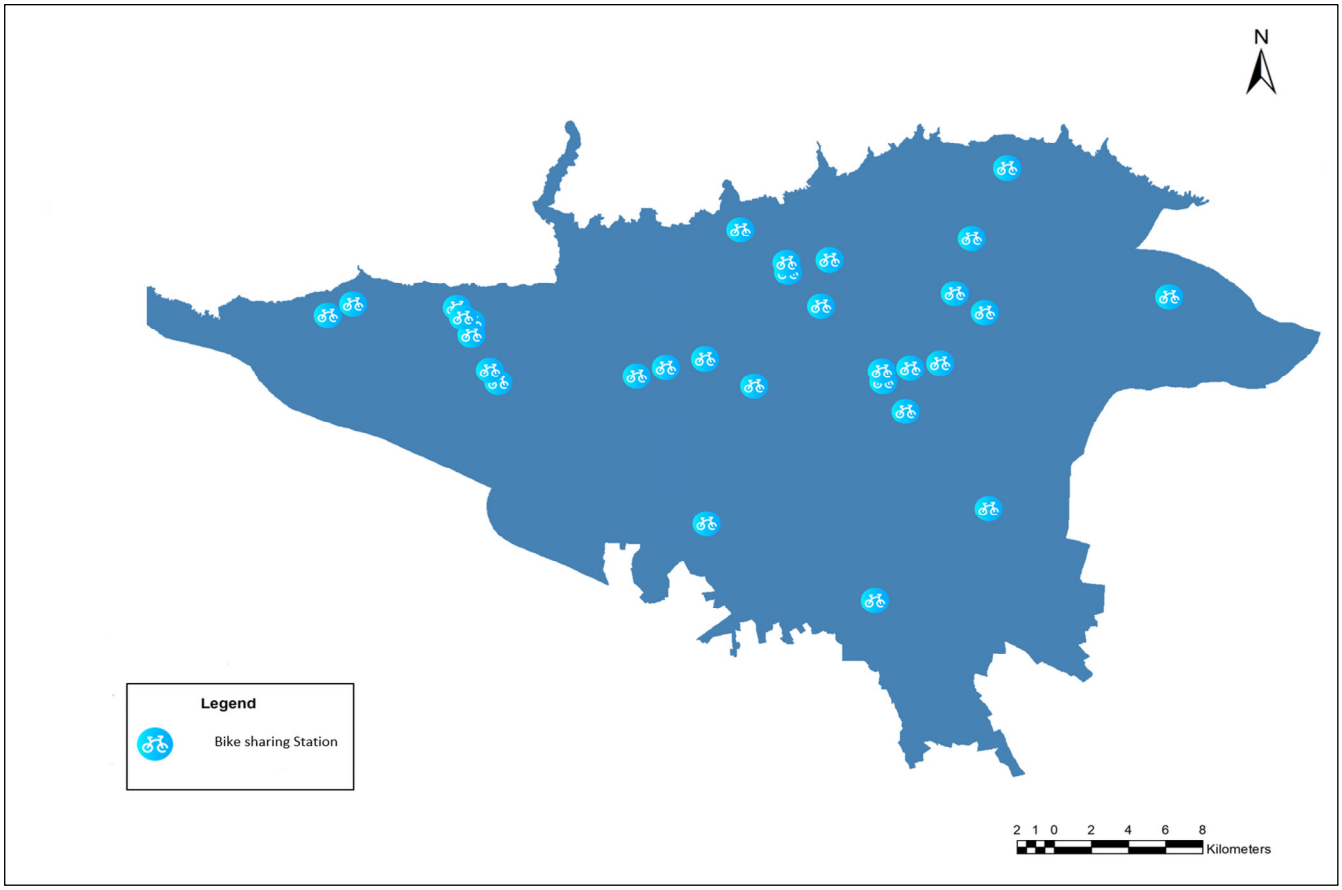


Figure 4. Overview of bike-sharing stations in Tehran.

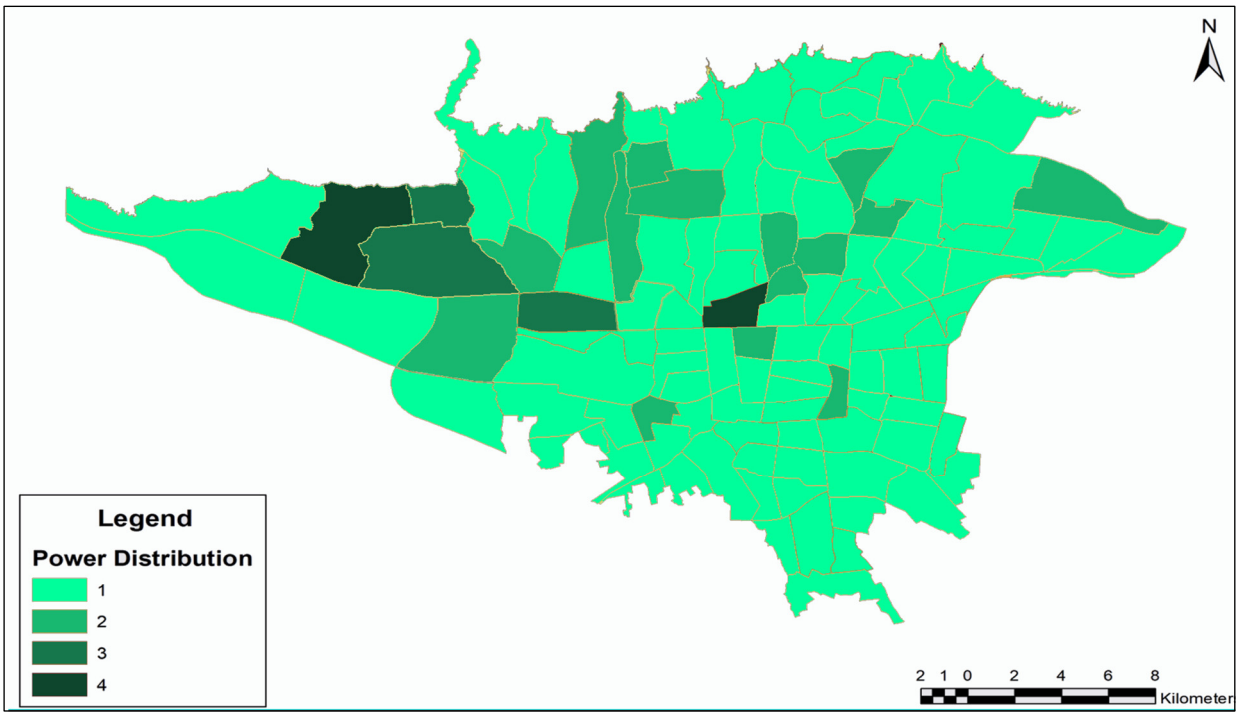


Figure 5. Spatial overview of BSS accessibility in Tehran.

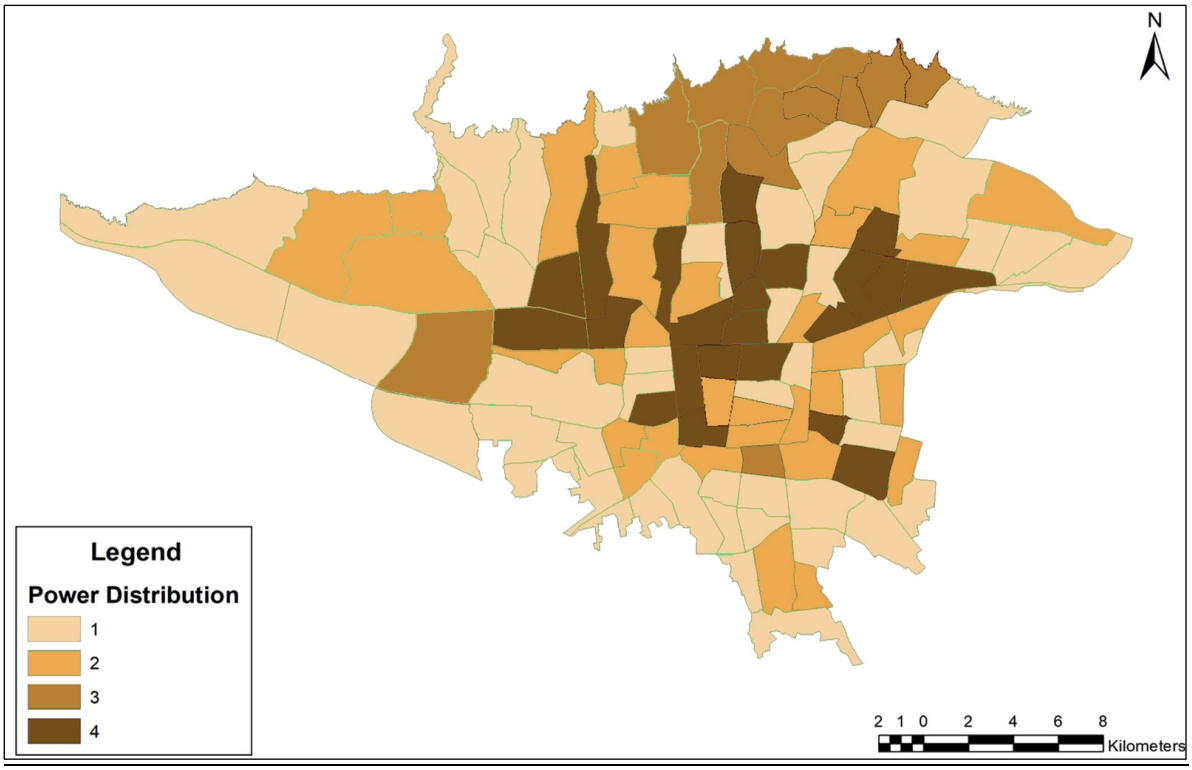


Figure 6. Accessibility distribution of the integrated PT and BSS.

4.4. Demand for Integrated PT and BSS in Tehran

To calculate the demand for the integrated PT and BSS system, data were extracted on the number of households without a car, low-income households, students, and the population aged over 16 years (due to the size of the bikes) in each TAZ. This information was obtained from the 2021 Population and Housing Statistics. After data collection, interviews with policymakers were conducted to determine the weights of these indicators.

Experts and policymakers involved in the projects participated in semi-structured interviews (total interviews = 28; declined participation = 7) to assign weights to each indicator. Eight initial interviewees were selected based on their roles and affiliations with the project using purposive sampling. Additional interviewees were identified through snowball sampling based on recommendations from previous participants. The main objective was to gather expert opinions on equity and transportation mode choice. Initial contact was made via email, and follow-ups were conducted by phone in case of no response. Most interviews were conducted in person at participants' workplaces, while eight were conducted by phone [52].

Interviewees included public sector staff from transit agencies and local governments, as well as consultants who actively participated in the projects. The interview process employed a variety of methods to investigate factors influencing the choice of transport mode. For instance, questions were asked about what influences the decision to use integrated PT and BSS as the primary mode of transportation (Appendix A).

The transcripts of the interviews and related documents were analyzed in several phases. The process began with a deductive approach, categorizing responses based on established concepts of equity and mode selection [53]. The next phase allowed themes and classifications to emerge from the interview data and related texts. In this context, Cope describes a method known as axial coding, which was applied. Axial coding focused on identifying key categories derived from broader topics related to mode selection (e.g., integrated PT and BSS) and mobility behavior (e.g., preference for integrated PT and BSS), while also allowing for codes to emerge from recurring patterns in the material, centered around a main category or axis [54]. Samples were coded by the researchers and reviewed to ensure consistency.

A summarizing method was utilized to examine the content of both interviews and written materials [54]. This method involved counting and interpreting word usage in relation to the study's research questions. Once the categories and labels were established, analytical software was employed to assess whether each interview record or document included a specific code. Summaries were then created for the interviews and documents—both in general and according to the interviewees' roles—that contained the relevant codes.

Weight derivation process:

During the interviews, experts were asked to rank each demand indicator according to its importance in determining integrated PT–BSS demand within Tehran's TAZs. Specifically, in questions 3.2 and 2.2 of the questionnaire, experts assigned a rank from 1 (most important) to 5 (least important) for each indicator. To convert these ranks into scores for weighting purposes, the following system was used: An indicator ranked 1 (highest importance) was assigned a score of 5, and an indicator ranked 5 (lowest importance) received a score of 1. Intermediate ranks were converted proportionally (e.g., rank 2 = score 4; rank 3 = score 3; rank 4 = score 2). For each indicator, the mean score across all expert responses was then calculated to derive its initial weight. To ensure comparability and that the total weights summed to 1.0, these mean scores were normalized by dividing each score by the total sum of all mean scores across the indicators. As an example, if an indicator's average converted score was 4.2 and all the indicators summed 21, then the final normalized weight was 4.2/21 = 0.20. These normalized weights were subsequently used to compute the weighted demand index for all TAZs during the demand appraisal phase. By using this approach, expert judgments directly informed the quantitative weighting of the demand indicators, while internal consistency, interpretability, and methodological robustness were maintained within the model framework.

Previous studies have identified several concerns associated with using interviews as a source of data. Respondents may withhold information or provide inaccurate answers without the interviewer realizing it, raising concerns regarding the dependability and credibility of the findings [52]. Another risk is that particularly persuasive participants may disproportionately shape the interpretation of events and dynamics—especially if they present themselves as neutral or impartial [53]. To mitigate these concerns, interviewees from various institutions and agencies were included, and their input was cross-verified with archival records, policy documents, and media reports.

Ultimately, by applying the approach outlined in this research, the demand for integrated PT–BSS within each TAZ was estimated. These demand values were then used, and the outcomes are illustrated in Figure 7. For easier interpretation and visualization, TAZs were grouped into four levels based on their need for integrated PT–BSS. The first quartile indicates the lowest level of demand, while the fourth quartile reflects the highest. As illustrated in the figure, most TAZs situated in the outskirts and southern parts of Tehran heavily depend on the combined PT–BSS system as their main mode of transportation.

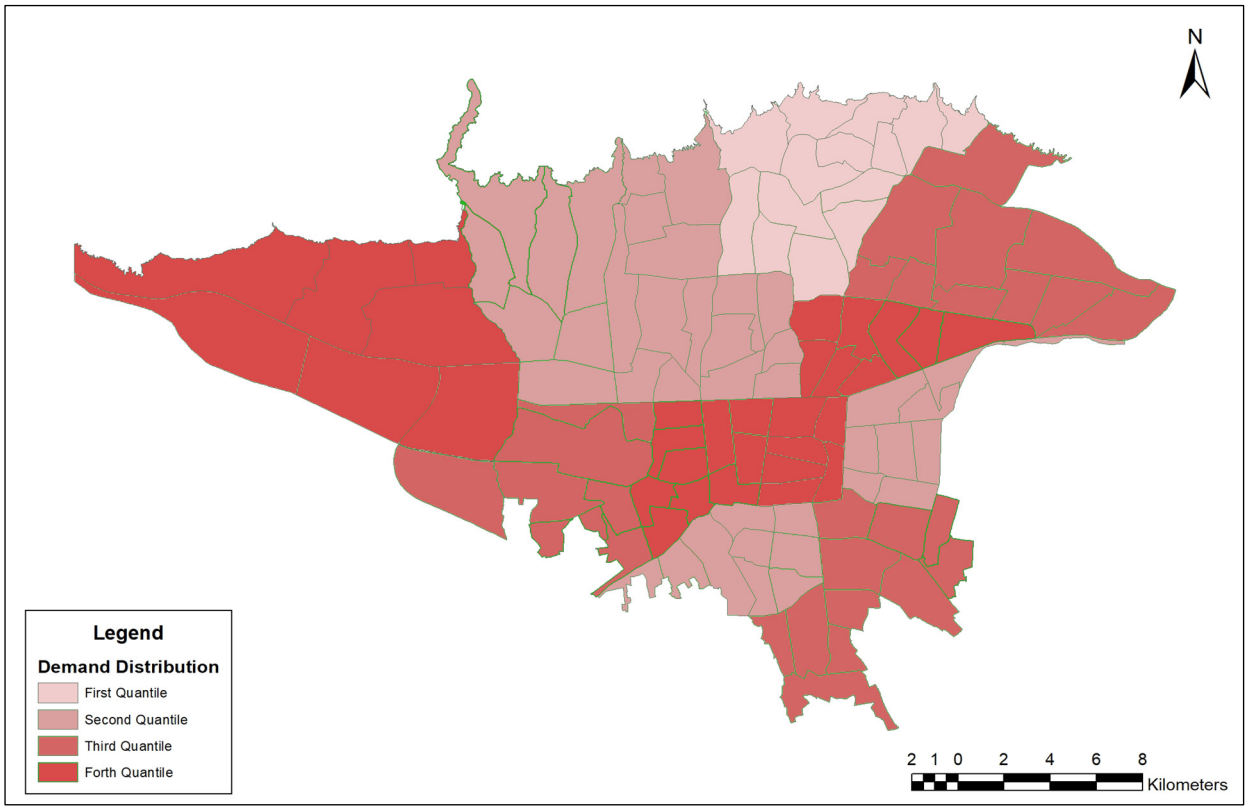


Figure 7. Demand distribution for the integrated PT and BSS.

4.5. Amount of the Balance in Demand and Supply (E_i)

The equilibrium between supply and demand is analyzed by comparing the need for public mobility options (demand) and the distribution of service power (supply) across TAZs. For this purpose, Equation (6) is applied. The E_i values for each TAZ are calculated based on current conditions, and the results are presented in Figure 8. To simplify interpretation, TAZs are divided into four categories based on the intensity of imbalance. The first quartile represents the lowest level of imbalance, while the fourth quartile indicates the highest. As shown in Figure 8, central and northern Tehran are generally better served by the integrated PT–BSS system, with E_i values frequently exceeding 1.2. This indicates over-supply, where the availability of service exceeds local demand. In contrast, several southern and western TAZs have E_i values below 0.8, indicating under-supply and insuffi-

cient accessibility relative to local needs. Since central TAZs already benefit from extensive access, the planning of new PT lines using BSS as a feeder mode to connect western and southern regions to the city center would help improve balance in service delivery. These results, derived from the calculated E_i balance index, demonstrate the practical application of the proposed framework to systematically identify spatial mismatches between supply and demand. This directly addresses the study's research questions and supports equitable, evidence-based decision-making in transport planning and investment. While in this study the 400 m buffers of BSS stations did not overlap across TAZ boundaries, the model structure allows for proportional distribution of station accessibility values in future cases where such overlaps may occur.

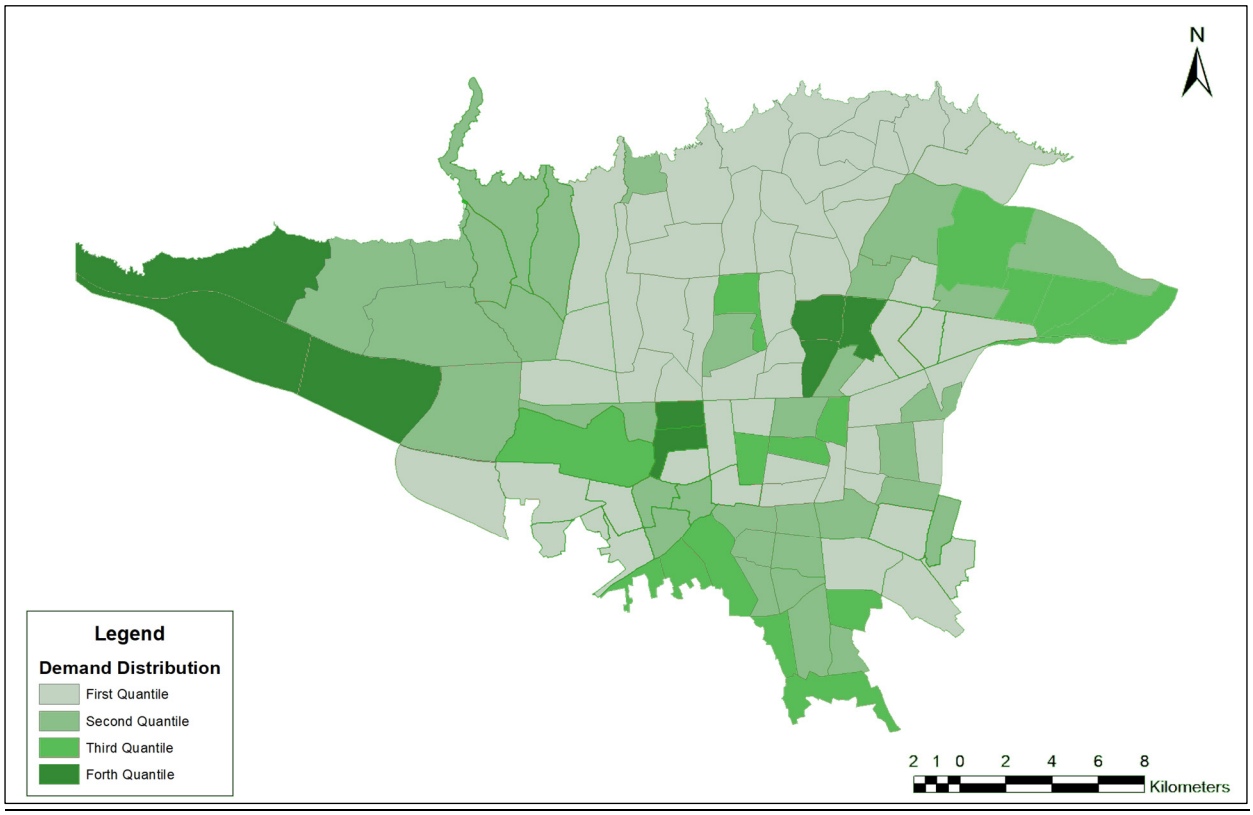


Figure 8. Spatial visualization of areas requiring the most improvement.

5. Conclusions

This study developed and applied a novel spatial evaluation framework to assess the balance between supply and demand in integrated PT and BSS in Tehran. The proposed framework consists of systematic calculations of PT and BSS accessibility, estimation of weighted demographic demand, and derivation of a spatial balance index (E_i), all integrated within a GIS environment to support prioritized urban transport planning.

PT accessibility was calculated based on the input–output power of transit stops, while BSS accessibility was measured by proximity to PT stations. These measures were combined with weighted demographic demand indicators derived from expert interviews. The results revealed substantial spatial inequities, with oversupplied central areas ($E_i > 1.2$) and underserved southern and western regions ($E_i < 0.8$).

By estimating the balance index (E_i) for each TAZ, the model identified priority areas for investment to improve equity and efficiency in urban mobility. These findings offer important insights for policymakers aiming to optimize investment decisions, reduce car dependency, and promote sustainable multimodal transportation.

Policy recommendations include increasing PT frequency and BSS coverage in car-scarce TAZs in the south and west, integrating first- and last-mile planning into PT expansion strategies, and reallocating funds from oversupplied central areas to underserved regions, ensuring more equitable network distribution.

This study contributes to the existing literature by addressing the lack of quantitative tools for integrated PT–BSS planning, enabling more balanced service provision and cost-effective infrastructure investments. Nevertheless, the study has limitations, such as reliance on 2021 cross-sectional data, uniform assumptions at the TAZ level, and the omission of temporal changes in travel behavior, which future studies should address.

Future research could expand this approach by incorporating temporal demand fluctuations and behavioral data to further advance integrated mobility planning and support the development of sustainable and equitable cities.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Interview protocol

1. Participant's Background

1.1. What position do you hold within the municipality, transit agency, or other relevant organizations?

1.2. For how many years have you held (or did you hold) this position?

2. Selecting PT

2.1. What are the advantages of utilizing PT in Tehran?

2.2. Please rank the following groups according to their likelihood of using public transportation as their main travel mode within Tehran's TAZ areas: (1) population of each TAZ; (2) people who do not own a car; (3) number of students; (4) people who earn a low income; (5) people with disabilities and people older than 60.

3. Choosing BSS

3.1. What advantages does using the BSS offer in Tehran?

3.2. Please order the following categories according to the likelihood of using BSS for first- and last-mile travel within Tehran's TAZs: (1) population of each TAZ; (2) people who do not own a car; (3) number of students; (4) people who earn a low income; (5) people with disabilities and people older than 60.

4. PT routes

4.1. Could you explain the method used to determine PT routes?

4.2. What key factors influenced the choice of the current station locations?

5. BSS stations

5.1. Can you describe the method used in choosing where to locate BSS stations?

5.2. What were the primary factors behind the selection of the existing stations?

6. Identifying and Evaluating Equity

6.1. How would you describe the concept of equity as applied to PT and BSS?
6.2. Was equity taken into account during the planning phase?
6.3. In what way was equity measured or evaluated?

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