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# How Bike-Sharing Affects the Accessibility Equity of Public Transit Systems—Evidence from Nanjing

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**Abstract:** This study examines how Free-Floating Bike-Sharing (FFBS) affects the accessibility equity of public transit sytems by serving as a first-mile feeder. To evaluate accessibility improvements for various opportunities within a 30-min travel time, we construct a complete travel chain approach based on multi-source, real-world data from Nanjing, China. The results indicate that FFBS significantly enhances accessibility, particularly for job opportunities and green spaces, with improvements of up to 180.02% and 155.82%, respectively. This integration also enhances the accessibility equity of public transit systems, particularly in green spaces, with a Gini coefficient improvement of 0.0336. Additionally, we find that areas with low housing prices exhibit greater accessibility inequality, while those with moderate housing prices benefit more from FFBS integration. These findings can potentially support transport planners in optimizing and managing FFBS and public transit systems to facilitate sustainable and inclusive transportation networks.

**Keywords:** micromobility; free-floating bike-sharing; accessibility equity; Lorenz curve; Gini coefficient

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## 1. Introduction

Rapid urbanization and increasing motorization have exacerbated traffic congestion and environmental degradation, leading to the unequal distribution of transportation resources across urban areas [1–3]. Public transit planning, which often prioritizes scale and efficiency, frequently overlooks the equity of transportation systems [4–6]. In response, scholars increasingly advocate for the integration of equity considerations into transportation planning, aiming to ensure that all urban residents benefit equally from mobility improvements [7,8].

Shared micromobility, particularly Free-Floating Bike-Sharing (FFBS), has emerged as a flexible, convenient, and environmentally friendly transportation option that offers a promising solution to urban mobility challenges [9–11]. As a form of shared micromobility, FFBS provides door-to-door service, making it an ideal choice for short-distance travel within urban areas [12,13]. Additionally, FFBS helps resolve the "first/last-mile"' problem by connecting residents to public transit systems, such as metro networks, thereby enhancing the overall efficiency and competitiveness of these systems [14]. Consequently, many cities worldwide have prioritized integrating FFBS with metro systems, with over half of shared bicycles in Chinese cities typically located near metro stations [15].

Integrating FFBS with public transit systems enhances the efficiency of "first/last-mile" travel and improves residents' overall accessibility to urban opportunities [16]. In urban planning, accessibility refers to how easily individuals can reach desired destinations or activities [17]. Accessibility, as a measure of transportation equity, is more comprehensive and impartial than traditional metrics, such as travel time savings, which often favor advantaged groups. Unlike conventional metrics, accessibility is independent of personal mobility constraints and unmet needs, providing a clearer measure of opportunity availability for all urban residents [18]. Furthermore, accessibility emphasizes the availability of opportunities rather than individuals' preferences or choices, highlighting its significance in assessing transportation equity [19].

While existing research has explored the accessibility benefits of FFBS, few studies have examined its impact on the equity of transportation systems, particularly with respect to its integration with metro networks. Accessibility equity refers to the principle that all individuals, regardless of socioeconomic background, should have equal access to essential services, resources, and opportunities [8,20]. Much of the existing literature on accessibility equity has focused primarily on job opportunities, neglecting other critical services such as healthcare, leisure, and green spaces [21]. A more comprehensive approach to accessibility, which considers a wide array of opportunities, is essential for fostering inclusive, sustainable urban environments. For example, job accessibility influences daily commuting behavior, while access to green spaces contributes to residents' physical and mental well-being, as well as fostering social interactions [22]. Therefore, assessing the equity of FFBS's impact on accessibility across diverse urban opportunities is crucial for a more holistic understanding of its role in urban mobility. Furthermore, many studies conceptualize FFBS as a substitute for walking, often in theoretical or simulated contexts, which may underestimate its true impact on accessibility equity in real-world settings [23]. By utilizing real-world travel data and actual travel times across the entire journey, this study aims to provide a more accurate and unbiased assessment of FFBS's impact on transportation equity.

This research addresses these gaps by examining the integration of FFBS with metro systems and its effects on accessibility equity within urban transportation. Using Nanjing as a case study, we explore the role of FFBS as a first-mile alternative to walking, enhancing access to six key urban opportunities: employment, healthcare, dining, shopping, leisure, and green spaces. The analysis leverages comprehensive real-world data, including job opportunities, housing prices, points of interest, and travel transactions from both the metro and FFBS systems. We aim to demonstrate that, in areas with limited transportation accessibility, the introduction of FFBS can significantly improve mobility, reduce disparities between peripheral and central urban areas, and enhance residents' social participation and quality of life. Moreover, the integration of FFBS with metro systems can optimize overall urban transportation efficiency, contributing to more balanced regional development.

To measure the equity of FFBS integration, this study evaluates changes in accessibility within Metro Station Affected Areas (MSAAs) across different housing price levels, using the Lorenz curve and Gini coefficient as equity metrics [24]. The findings aim to clarify FFBS's contribution to the equity of existing transit systems, providing valuable insights for promoting sustainable, inclusive, and livable urban environments. Specifically, we mainly address the following issues:

1. How does the integration of Free-Floating Bike-Sharing (FFBS) with metro systems affect the accessibility equity of public transit systems?
2. To what extent does FFBS reduce spatial disparities in the accessibility of public transit systems between central and peripheral urban areas?
3. How does FFBS integration impact transportation accessibility and equity across different socioeconomic groups?
4. How can the Lorenz curve and Gini coefficient be used to assess changes in transportation accessibility equity before and after FFBS integration?

The remainder of this paper is structured as follows: Section 2 provides a literature review of relevant studies on metro station-based accessibility, accessibility equity indices, and the impact of bike-sharing systems on the equity of public transit systems. Section 3 describes the multi-source data used in the analysis. Section 4 outlines the methodology for estimating public transit travel times, evaluating the impact of bike-sharing on accessibility and assessing accessibility equity. Section 5 presents the results and discussion. Section 6 concludes with remarks and outlines future research directions.

## 2. Literature Review

### 2.1. Accessibility Based on Metro Stations

Studies on public transit accessibility can generally be categorized into two types: those that evaluate accessibility based on the transit network and those that focus on transit stations [25]. Unlike studies focusing on the transit network, those focusing on transit stations enable the use of buffers to link stations with their surrounding areas and offer the ability to focus on specific areas or individual stations. Ann et al. [26] examined the variations in the impacts of different transportation modes on multi-modal accessibility at metro stations in Delhi, India. They incorporated distance decay effects and conducted a comparative analysis of accessibility across various modes, contributing to TOD planning in Delhi. Yang et al. [27] investigated the overall accessibility of the public transportation system, focusing on the environment surrounding transportation stations, including rail transit stations, and the system's configuration. They developed an accessibility model and applied it to analyze public transportation accessibility at the community level in Wuhan. Li et al. [28] investigated the accessibility of Xi'an metro stations from two perspectives, providing guidance for improving station surroundings and layouts. The first assessed station attractiveness, measuring ease of access via different modes, while the second evaluated station radiation, measuring interconnectivity between stations. Building on these advantages, this study aims to assess the accessibility of public transit systems based on metro stations. This approach considers both the connectivity pathways and the facilities available for activities near metro stations.

### 2.2. Accessibility Equity Indices

Equity studies in transportation can be broadly classified into two types: quantitative analysis using equity indices and qualitative analysis using spatial analysis tools [29]. The first type combines accessibility indices, derived from accessibility analyses across regions, with population data to compute an equity index for evaluation. The second type overlays transportation accessibility or supply data with spatial regions and population data to assess spatial equity [30]. Most scholars use equity indices for quantitative analysis, with the Lorenz curve, Gini coefficient, and Theil index being the most commonly employed [24,31].

Several scholars use the Gini coefficient and Lorenz curve to assess accessibility equity. For example, Delbosc and Currie [32] used these tools to assess the fairness of transportation resource allocation in Melbourne, focusing on vertical equity among different population groups, including car and non-car owners. Giannotti et al. [33] compared public transportation accessibility in São Paulo and London using the Lorenz curve and Gini coefficient, finding greater accessibility inequities in São Paulo. Lope and Dolgun [34] analyzed the equity of tram services for vulnerable groups (e.g., elderly and disabled) in Melbourne using the Lorenz curve and Gini coefficient, revealing notable service disparities for disabled individuals. Jang et al. [35] assessed public transportation accessibility in Seoul using the Lorenz curve and Gini coefficient, analyzing equity changes before and after new metro lines were introduced.

Several scholars use the Theil index to assess accessibility equity. For instance, Camporeale et al. [36] evaluated multimodal transportation accessibility using the Theil index, which measures equity across time, space, and travel groups. Souche et al. [37] used the Theil index and other measures to study income concentration and accessibility inequity in Lyon, France, finding that the introduction of tolls could reduce suburban inequities.

Hamidi et al. [38] investigated cycling accessibility in Malmö, Sweden, using the Theil index and other metrics to measure access to bicycles at public transport hubs, exploring transportation equity from both modal and spatial perspectives.

Existing research has established that equity indices are central to quantitative analyses of accessibility equity. This method quantitatively assesses inequities across areas and transportation modes, providing objective results. This study will therefore use the Lorenz curve and Gini coefficient to evaluate the accessibility equity of various travel destinations across different areas.

### *2.3. Impacts of Shared Micromobility on the Accessibility and Equity of Public Transit Systems*

The "first/last-mile" challenge in public transit systems has gained significant attention in recent years. Research suggests that shared micromobility can effectively address this longstanding issue by replacing walking with more efficient modes, thereby enhancing terminal travel efficiency [16].

Research indicates that bike-sharing can effectively address this long-standing issue by replacing walking with more efficient cycling, thus improving terminal travel efficiency [16]. Numerous scholars have investigated the relative impact of cycling versus walking on the effectiveness of the "first/last-mile" segment of public transit systems. For example, Jäppinen et al. [39] found that cycling reduces transit travel time by an average of 6 min (about 10% of total travel time), thereby improving competitiveness. Other studies have shown that the higher speed of cycling, compared to walking, significantly expands the coverage area around transit stations [40]. Specifically, the influence area of cycling is more than three times that of walking [41]. Lei and Church [42] and Mavoa et al. [43] evaluated accessibility by considering the number of opportunities accessible within a specified time and monetary cost, accounting for both last-mile travel time and total public transit time. Studies on urban rail transit [44] and surface buses [45] have confirmed that replacing walking with cycling for the last mile significantly enhances station accessibility, leading to a 43.7% increase in employment accessibility. Wang et al. [46] studied Beijing's bike-sharing system and concluded that integrating bike-sharing with public transit significantly reduces commuting time and enhances job accessibility.

Other researchers have explored the relative impact of shared electric mobility compared to walking on the effectiveness of the "first/last-mile" segment of public transit systems. Hosseini et al. [47] evaluated shared electric mobility hubs (eHUBs) in Inverness, finding that population density and weather influence demand, while proximity to public transport has a minimal effect. This suggests that e-bikes are better suited for longer trips than as complements to public transport. Hosseini et al. [48] also assessed Dublin's e-bike sharing system using data envelopment analysis, concluding that expanding the system and improving infrastructure could enhance eco-efficiency and ridership. The study stresses the need to shift from car-centric policies to more sustainable, inclusive alternatives. McQueen and Clifton [49] found that e-scooters did not improve racial or gender equity in transportation and were less efficient than bikes or cars for multimodal trips, though policy changes like parking pricing and fare adjustments could boost their use. Zuniga-Garcia et al. [50] modeled the interaction between e-scooters and bus transit in Austin, using surveys and datasets to analyze demand patterns, user characteristics, and mode shift, with a two-stage regression method to account for confounding factors.

However, most studies focus on the impact of replacing walking with cycling in the first/last-mile segment on the accessibility and equity of public transit systems, with few using real-world cycling data, such as bike-sharing, to assess these effects. This study uses transaction data from free-floating bike-sharing and public transit systems to quantitatively assess the impact of bike-sharing on the accessibility and equity of public transit systems.

## 3. Study Area and Data Preparation

### 3.1. Study Area

This study focuses on Nanjing, the capital of Jiangsu Province, which is located in eastern China, centrally positioned in the lower Yangtze River region. Nanjing plays a key role as a national gateway, facilitating the Yangtze River Delta's efforts to promote development in the central and western regions. It is geographically located between latitudes 31°14′ N and 32°37′ N and longitudes 118°22′ E and 119°14′ E. The coordinates of the city center, Xinjiekou, are 32°02′38″ N and 118°46′43″ E. Nanjing spans an area of 6587 km$^2$, with an urban built-up area of 868 km$^2$ [51]. As of October 2020, the metro network covers most of Nanjing, with multiple lines in operation and a total length exceeding 400 km. These metro lines link the city's primary urban centers, commercial zones, residential districts, and some suburban areas, forming an efficient and convenient urban transit network, as shown in Figure 1.

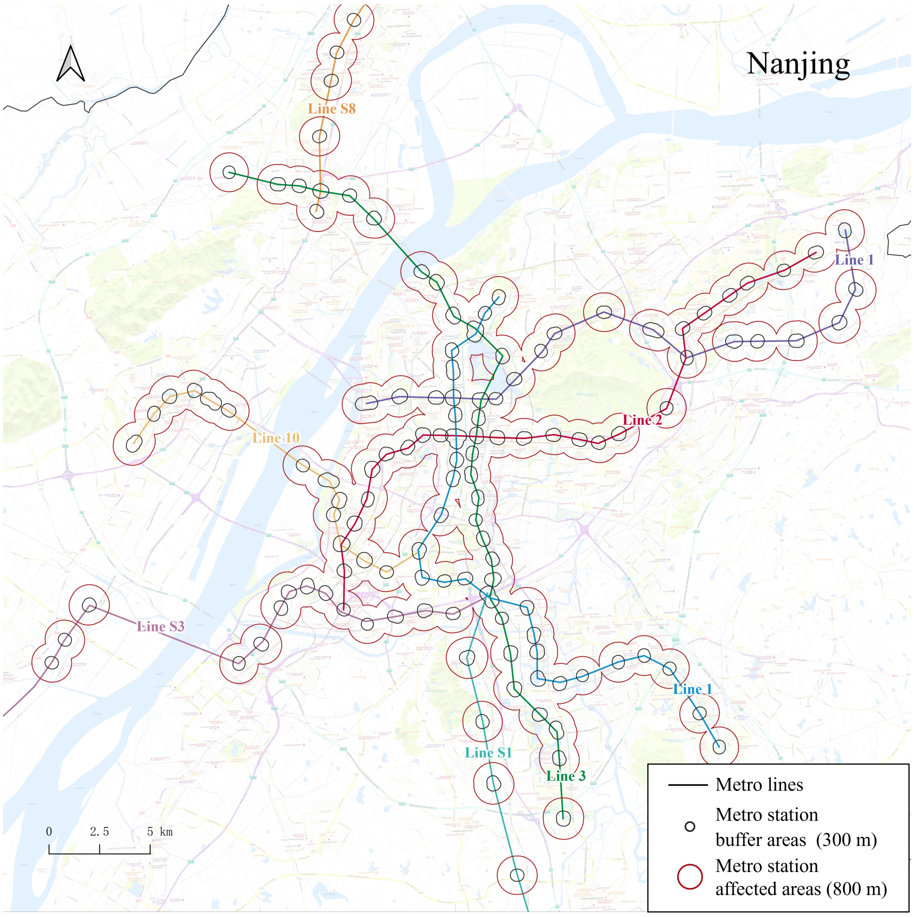



**Figure 1.** Study area.

This study analyzes accessibility using data from nine selected metro lines and 142 stations in Nanjing. Building on previous studies [52], metro passengers typically search for feeder buses within a 300 m transfer distance. Therefore, this study uses Metro Station Buffer Zones (300 m) around metro stations to examine modal integration with bike-sharing. Based on previous studies [53], the spatial range of a transit-oriented development area is typically defined by the walking distance from home to the transit station, usually ranging from 400 to 800 m for most transferring travelers. Accordingly, Metro Station Affected Areas (800 m) around metro stations are used to calculate the average housing prices in the surrounding neighborhoods. Housing prices are used as an indicator of the economic context, which will be discussed in detail in Section 3.2.1.

Nanjing implemented FFBS in 2016, motivated by its convenience for short-distance trips and its complementary role to the existing public transit system [54]. The city's extensive network of bicycle lanes and pedestrian-friendly streets offers safe and convenient routes for FFBS users. By October 2020, three FFBS companies were operating in Nanjing: Mobike, Hellobike, and Didibike. The FFBS regulatory platform in Nanjing manages 71,135 bikes from Mobike, 44,623 from Hellobike, and 121,074 from Didibike [55]. From 12 October to 1 November 2020, the platform recorded 11.67 million orders, averaging 3.89 million orders per week.

Nanjing's well-designed urban layout, extensive metro system, and rich FFBS usage data make it an ideal case for studying the impact of bike-sharing on the accessibility and equity of public transit systems.

### *3.2. Data Description and Preparation*

The data used in this study include raster data on job opportunities and housing prices, points-of-interest data, and transaction data for both the metro and FFBS systems.

#### 3.2.1. Raster Data on Job Opportunities and Housing Prices

Raster data on job opportunities are derived from mobile phone data records produced by Hangzhou Zhejiang Cheng Data Technology Co., Ltd. (Hangzhou, China), which document the number of job opportunities within 200 m × 200 m grids. A total of 3939 job grids are mapped, with their centroids serving as reference points for measuring job accessibility. Similarly, housing prices produced by Beike Technology Co., Ltd. (Tianjin, China) are recorded at the same grid granularity, providing insights into the socioeconomic context. Housing price data are sourced from domestic real estate platforms and aggregated into 200 m × 200 m grids by calculating the average price within each grid. Both the raster data on job opportunities and the housing price data were collected in October 2020.

#### 3.2.2. Points-of-Interest Data

The Points-Of-Interest (POI) data for this study are obtained from online mapping services, specifically Baidu Maps. Each entry includes coordinates, name, address, and category. These data are used to assess the availability of opportunities within public transit systems. Specifically, this study examines healthcare, dining, shopping, leisure, and green spaces as key travel destinations. This paper uses POI data for Nanjing from 2020, with the POI data fields shown in Table 1.

**Table 1.** POI data fields.

| Field Name | Description | Sample Data |
|---|---|---|
| FID_POI | Identification number of POI | 431,096 |
| Name | POI name | Jiushixiaochu |
| Category | Category of POI | Restaurant |
| Subcategory | Subcategory of POI | Chinese food |
| Lat | Latitude of POI | 121.30934 |
| Lng | Longitude of POI | 31.180236 |

#### 3.2.3. Transaction Data from the Metro System and the FFBS System

To investigate the extent of bike-sharing use in modal integration with public transit, we collected transaction data from both the metro and FFBS systems. The metro transaction data include details of passenger entries and exits at each station. By processing and analyzing these data, passenger inflow and outflow at each station can be quantified. The FFBS transaction data include information on bike rentals and returns. Spatiotemporal matching allows for the identification of FFBS trips that connect to metro stations. All transaction data were collected on 7 July 2020 (Tuesday), 8 July 2020 (Wednesday), and 9 July 2020 (Thursday), with the corresponding data fields shown in Tables 2 and 3.

**Table 2.** Transaction data on metro trips.

| Field Name | Description | Sample Data |
|---|---|---|
| ALIASCARDNO | Card Number | E0************ |
| CARDTYPE | Card Type | 3 |
| GETONTIME | Entry Time | 8 July 2020 08:00:00 |
| GETONOFFDATETIME | Exit Time | 8 July 2020 08:09:20 |
| GETONSTATIONID | Entry Station ID | 7 |
| STATIONID | Exit Station ID | 17 |
| PAYMENTAMOUNT | Transaction Amount (CNY) | 2.85 |

Note: the sample data of ALIASCARDNO has been masked.

**Table 3.** Transaction data on FFBS trips.

| Field Name | Description | Sample Data |
|---|---|---|
| JOURNEY ID | Identification of the journey | 14343637 |
| BIKE ID | Identification of the bike | didibike1153273458113216233 |
| DEPARTURE TIME | Departure time of bike ride | 8 July 2020 10:00:16 |
| ARRIVAL TIME | Arrival time of bike ride | 8 July 2020 10:00:16 |
| ORIGIN_LNG | Longitude of pickup point | 118.79564813 |
| ORIGIN_LAT | Latitude of pickup point | 32.02617477 |
| DESTINATION_LNG | Longitude of drop-off point Longitude | 118.7952026 |
| DESTINATION_LAT | Latitude of drop-off point | 32.02467072 |

## 4. Method

The methodological framework, shown in Figure 2, comprises three components. First, we evaluate the facility accessibility of public transit systems without FFBS integration. Second, we assess the facility accessibility of public transit systems with FFBS integration and measure the improvements in accessibility enabled by FFBS. Third, we analyze the accessibility equity of public transit systems with and without FFBS integration and examine the effect of FFBS on accessibility equity.

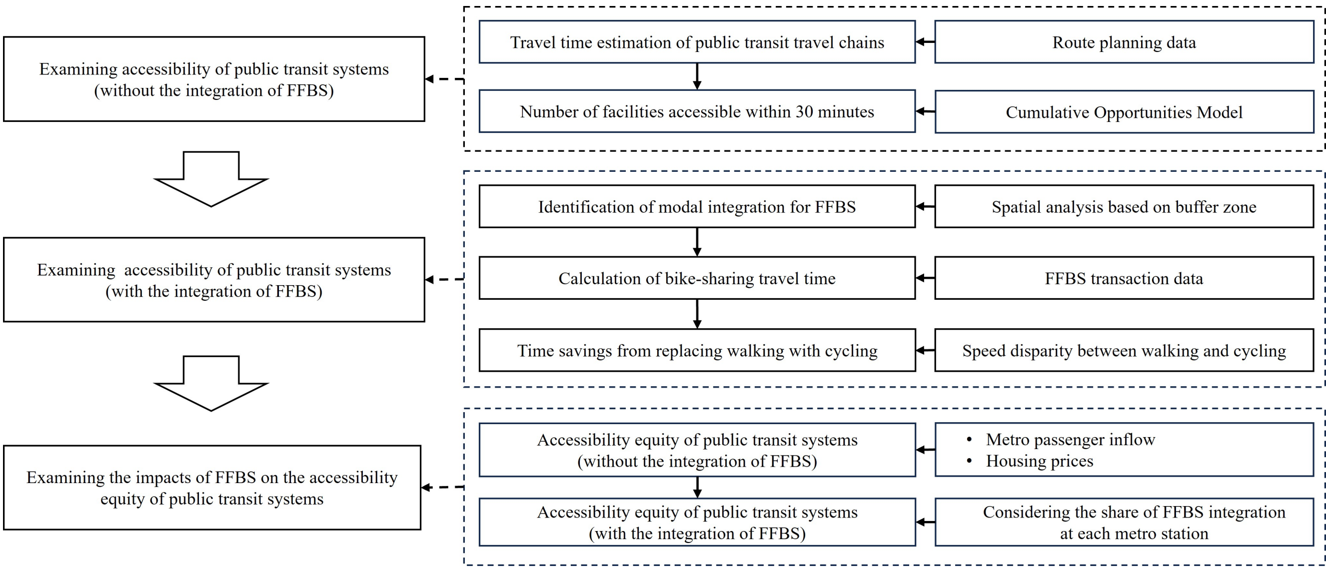



**Figure 2.** Methodological framework.

*4.1. Accessibility Estimation of the Metro System*

4.1.1. Travel Time Estimation of Public Transit Travel Chains

Previous research on accessibility to public service facilities often uses distance-based cost measures, such as Euclidean, Manhattan, network, and raster cost distances, to estimate travel time between residents' origins and destinations. However, the GIS network analysis approach fails to adequately address the following issues:

1. Fixed timetables and routes of public transit systems.
2. Variable transfer and waiting times between transit stops.
3. The "first/last-mile" problem, including walking or cycling time to and from transit stations.

The availability of open data on the internet offers new opportunities to calculate travel times within public transit networks. This study uses an internet map routing API and adopts a "complete travel chain" approach to calculate residents' travel time costs. This method relies on real-time road networks and accounts for various time expenditures, such as traffic congestion, parking searches, vehicle retrieval, transfers, waiting times, and walking. Consequently, it accurately reflects residents' actual travel experiences. Furthermore, this approach eliminates the need for the data collection and updates typically required in traditional GIS-based traffic network models.

This study uses transaction data from FFBS and route planning data for public transit to estimate the total travel time of the public transit travel chain, as shown in Figure 3. The public transit travel chain includes two stages: (1) the first stage covers the first-mile trip from the origin to the metro station; (2) the second stage involves the journey within the public transit system and the last-mile trip. Mode 1 assumes walking is used for first-mile connections, whereas Mode 2 assumes FFBS is used for the same. This study considers both cycling and walking as potential first-mile travel modes.

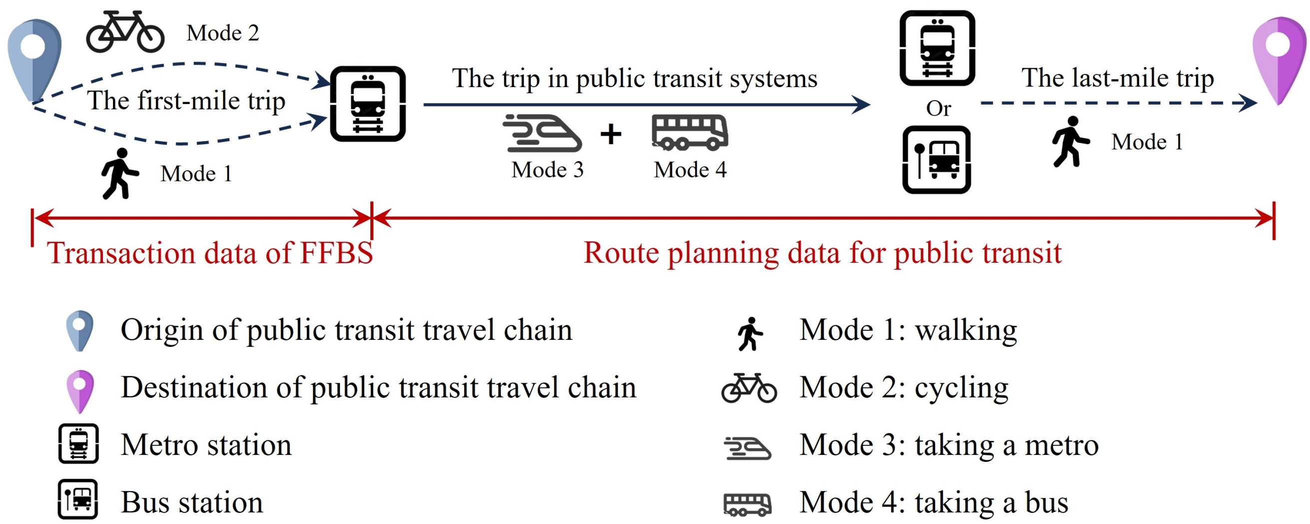



**Figure 3.** A complete public transit travel chain based on metro stations. We assume that travelers either choose to walk (Mode 1) or use FFBS (Mode 2) to access metro stations, while the remainder of the journey is completed through route planning for public transit, which includes other modes, like buses.

The "complete travel chain" method for calculating travel time can be used to quantify the travel time cost associated with metro-based public transit as follows:

$$t_{od}^{m} = T_{oi}^{m} + T_{ij}^{transit} + T_{jd}^{m}, \tag{1}$$

$$T_{ij}^{transit} = T_{ij}^{in-vehicle} + T_{ij}^{waiting} + T_{ij}^{transfer}, \tag{2}$$

where $t_{od}^{m}$ represents the total travel time for a traveler to reach destination $d$ from origin $o$ using mode $m$. This term represents the total duration of the public transit travel chain. In this context, $m$ denotes the first-mile travel strategy chosen by the traveler. When $m = 1$, the traveler uses walking to access the metro station; otherwise, cycling is employed. $T_{ij}^{transit}$ represents the total travel time from the initial metro station to the final destination. This duration includes $T_{ij}^{in-vehicle}$ (in-vehicle time), $T_{ij}^{waiting}$ (waiting time), and $T_{ij}^{transfer}$ (transfer time). $T_{oi}^{m}$ and $T_{jd}^{m}$ represent the time spent on the first- and last-mile connections under travel mode choice $m$, respectively.

This study investigates the accessibility of facilities within public transit systems, based on metro stations, using a time cost matrix. The origin points consist of 142 metro stations in Nanjing, and 1 km × 1 km square grids surrounding these stations are used to calculate public transit travel times from each metro station to each grid via public transit route planning.

#### 4.1.2. Cumulative Opportunities Model

The cumulative opportunities model, used to assess location-based accessibility, calculates the total number of opportunities accessible to travelers within a specified travel cost for a given transportation mode [56]. A higher number of accessible opportunities reflects greater accessibility. These opportunities usually encompass essential urban services, such as jobs, healthcare, dining, shopping, leisure, and green spaces. The cumulative opportunities model is easy to implement and provides high interpretability, facilitating a clear analysis of the relationship between transportation and land use. Consequently, it is widely used in accessibility studies [57]. The formulation of the cumulative opportunities model applied in this study is as follows:

$$A_i^m = \sum_{j=1}^{n} OP_i^m (t_{od}^m \leq T_{max}), \quad (3)$$

$$m = 1(\text{walking}), m = 2(\text{cycling}), \quad (4)$$

where $A_i^m$ represents public transit accessibility based on metro station $i$ for the first-mile trip under travel mode $m$ and $OP_i^m$ represents the number of various travel destinations accessible from metro station $i$ within a maximum travel time (set to 30 min) under mode $m$.

### *4.2. Impact of FFBS on the Accessibility of the Pulic Transit System*

#### 4.2.1. Identify Modal Integration Trips for FFBS

FFBS trips connecting to metro stations can be classified into three main types: Mdal Substitution (MS), Modal Integration (MI), and Modal Complementation (MC) [58]. Modal Substitution (MS) occurs when FFBS trips replace public transit trips. Modal Integration (MI) refers to the use of FFBS as a connecting mode to access metro stations. Modal Complementation (MC) occurs when FFBS is used to complement public transit in areas with limited coverage. The distance and duration of the FFBS journey are key factors in distinguishing MS, MI, and MC.

To evaluate these criteria, the study starts with a buffer analysis (see Figure 4) to identify two primary scenarios for FFBS trips: (1) Scenario 1 includes trips starting in Zone A and ending in either Zone A or Zone B, or starting in Zone B and ending in Zone A. These trips typically integrate with public transit to reduce metro transfers. (2) Scenario 2 involves trips between Zone A and Zone C, emphasizing the potential for modal integration with public transit. Additional scenarios consider FFBS as Modal Substitution (MS) or Modal Complementation (MC). In the second step, trip durations are analyzed, classifying trips under 30 min as MI trips and trips exceeding 30 min as recreational. These MI trips connect metro-underserved areas to the nearest stations. The number of daily MI trips and the average travel time for each metro station are then calculated.

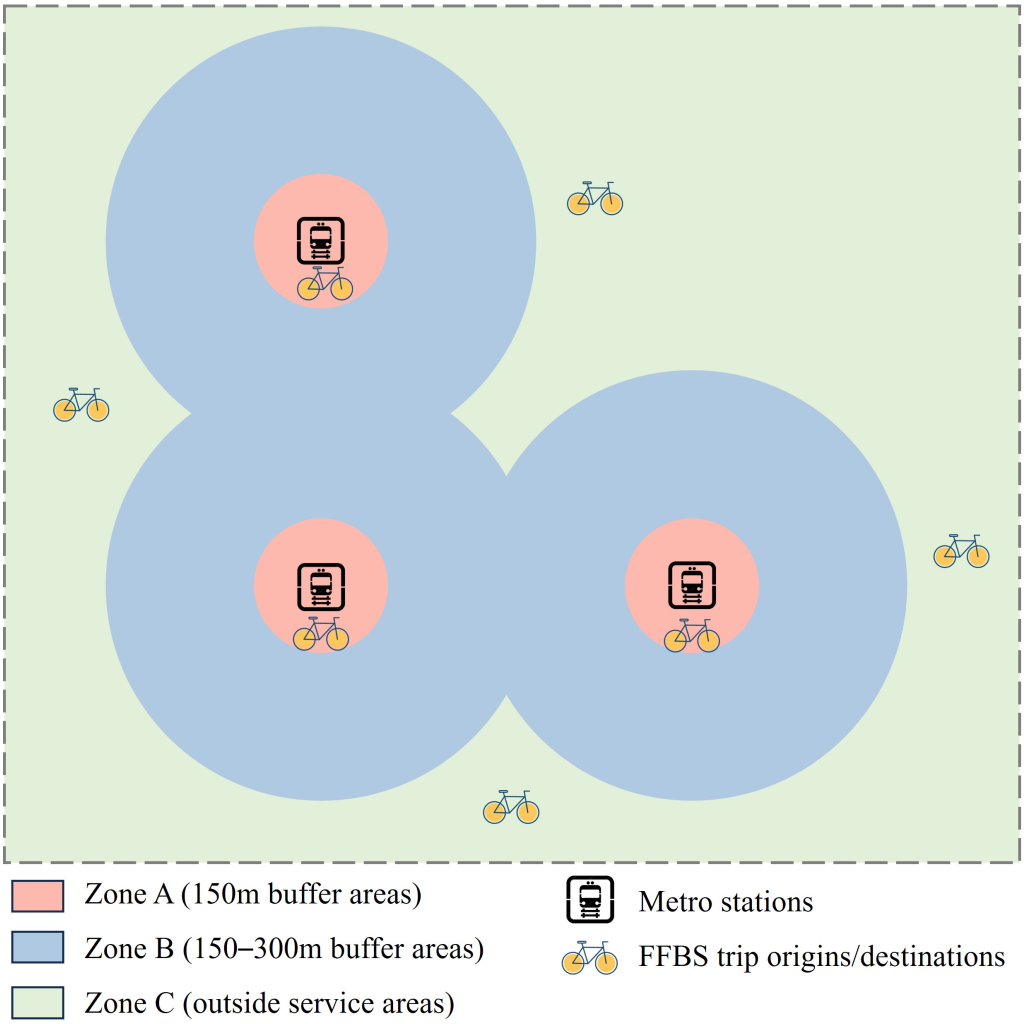



**Figure 4.** Identifying modal integration trips of FFBS.

4.2.2. Accessibility Estimation of the Public Transit System with FFBS Integration

Enhancing first/last-mile travel efficiency improves public transit accessibility, especially when cycling replaces walking. This improvement can be quantified using relative ratios to measure the increase in accessible opportunities [45]. Cycling is typically three times faster than walking [44]. Accounting for the time spent borrowing and returning an FFBS bike, the time saved by cycling is about 1.5 times the cycling trip duration. This time saving enables passengers to cover longer distances within the same timeframe, thus increasing the number of accessible opportunities. The percentage increase in accessibility when cycling replaces walking can be calculated as follows:

$$P_i = \frac{A_i^2 - A_i^1}{A_i^1}, \tag{5}$$

where $P_i^m$ represents the percentage increase in accessibility of public transit systems based on metro station $i$, $A_2^m$ represents the public transit accessibility for the first-mile trip to metro station $i$ using cycling, and $A_1^m$ represents the public transit accessibility for the first-mile trip to metro station $i$ using walking.

*4.3. Evaluation of Accessibility Equity*

Figure 5 depicts a typical Lorenz curve. The horizontal axis represents the cumulative share of individuals, ranked from lowest to highest income, while the vertical axis shows the cumulative share of total income. The straight line in this diagram represents the line of equity, reflecting an ideal distribution in which, for instance, 50% of the population holds 50% of the total income. The Lorenz curve, typically lying below the equity line, represents the actual income distribution. The Gini coefficient, derived from the Lorenz curve, quantifies inequality by comparing the area between the equity line and the Lorenz curve to the total area under the equity line. It ranges from 0 to 1, where a higher Gini coefficient indicates greater inequality (with a Lorenz curve farther from the equity line), and a lower coefficient signifies a more equitable distribution (with a curve closer to the equity line). The Gini coefficient is calculated as follows:

$$G = 1 - \sum_{p=1}^{P} \left(X_p - X_{p-1}\right)\left(Y_p + Y_{p-1}\right), \quad (6)$$

where $G$ represents the Gini coefficient, $X_p$ represents the cumulative share of the first $p$ research units, $Y_p$ represents the cumulative share of facility accessibility of the first $p$ research units, and $P$ represents the total number of research units.

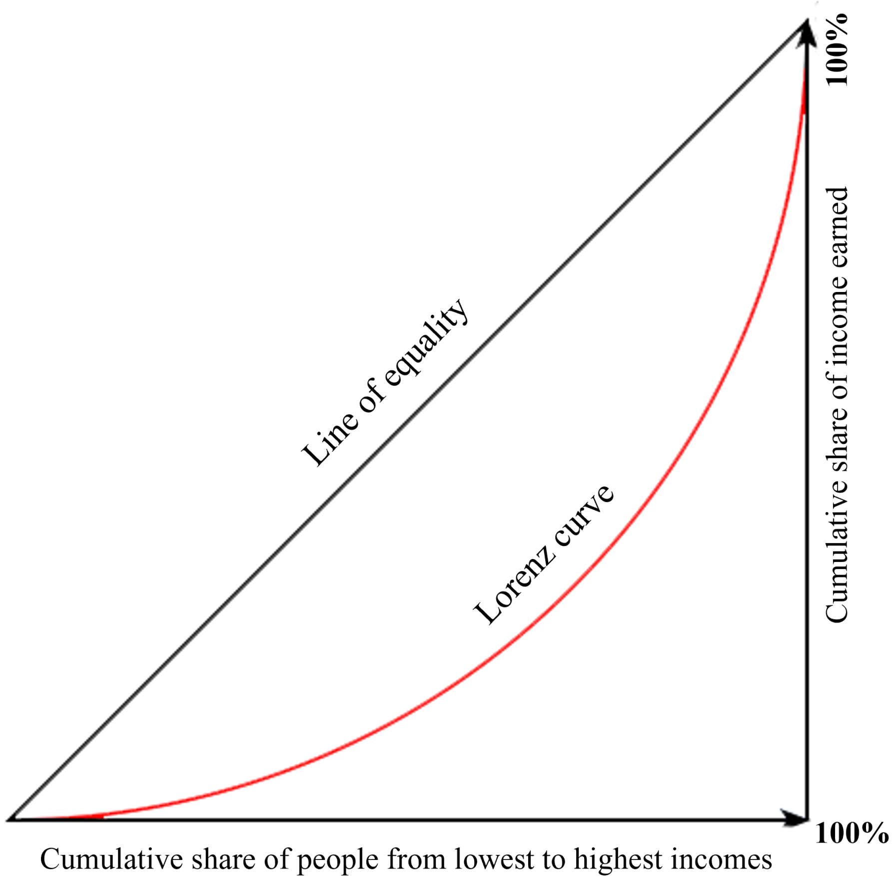



**Figure 5.** Schematic diagram of the Lorenz curve.

To assess the accessibility equity of public transit systems, we propose a quantitative approach based on the Gini coefficient, which measures the inequality in the distribution of passengers' access to stations and facilities. The methodology accounts for both passenger inflow at each station and accessibility to key destinations, considering two scenarios: one without FFBS integration and one with FFBS integration. The Gini coefficient is influenced by passenger inflow at metro stations and the usage of FFBS for Modal Integration (MI) at these stations. The Gini coefficient, denoted as $G^m$, is calculated using the following formulas:

$$X_p^m = \frac{\sum_{i=1}^{p}(N_i^{inflow})}{\sum_{i=1}^{P}(N_i^{inflow})} \times 100\%, \quad (7)$$

$$Y_p^1 = \frac{\sum_{i=1}^{p}(N_i^{inflow} A_i^1)}{\sum_{i=1}^{P}(N_i^{inflow} A_i^1)} \times 100\%, \quad (8)$$

$$Y_p^2 = \frac{\sum_{i=1}^{p}((N_i^{inflow} - N_i^{MI})A_i^1 + N_i^{MI} A_i^1)}{\sum_{i=1}^{P}((N_i^{inflow} - N_i^{MI})A_i^1 + N_i^{MI} A_i^1)} \times 100\%, \quad (9)$$

$$G^m = 1 - \sum_{p=1}^{P}\left(X_p^m - X_{p-1}^m\right)\left(Y_p^m + Y_{p-1}^m\right), \quad (10)$$

$$m = 1(\text{without FFBS integration}), m = 2(\text{with FFBS integration}),$$

where $G^m$ represents the Gini coefficient under mode $m$, $X_p^m$ represents the cumulative share of the first $p$ research units, $Y_p^m$ represents the cumulative share of facility accessibility of the first $p$ research units, $N_i^{inflow}$ represents the passenger inflow of the $i$-th metro station, and $N_i^{MI}$ represents the FFBS usage for MI at the $i$-th metro station.

## 5. Results and Discussion

First, we present statistical results on facility accessibility at metro stations and evaluate the improvement in accessibility when walking is replaced by FFBS. Second, we examine the impact of FFBS on the accessibility equity of public transit systems across six types of travel destination. Additionally, we investigate whether or not this impact exhibits any bias towards Metro Station Affected Areas (MSAAs) with varying housing prices.

### *5.1. Public Transit Accessibility for Various Travel Destinations*

#### 5.1.1. Spatial Distribution of Public Transit Accessibility Based on Metro Stations

The cumulative opportunity model provides a robust framework for calculating metro accessibility across various travel destinations, evaluating how different areas of a city are served by public transit. The spatial distribution of accessibility within a 30-min travel time, shown in Figure 6, reveals a clear pattern: central urban areas, particularly around Xinjiekou, exhibit significantly higher accessibility than the outskirts. This pattern is common in metropolitan transportation systems, where central business districts and major transit hubs typically benefit from superior connectivity due to the concentration of key amenities and high-density development.

The spatial distribution of accessibility is essential for identifying gaps in service coverage, particularly in peripheral or underserved neighborhoods. The gradual decline in accessibility away from the city center highlights areas where public transit services could be expanded or improved. This pattern highlights the need for strategic planning to improve transit access across urban zones, especially for residents in lower-access areas. Enhancing first-mile travel efficiency—particularly through active modes like cycling—can optimize the overall performance of the metro system. This is especially relevant for addressing the "last mile" problem, where the convenience and affordability of metro station connections can significantly influence public transit usage and overall accessibility.

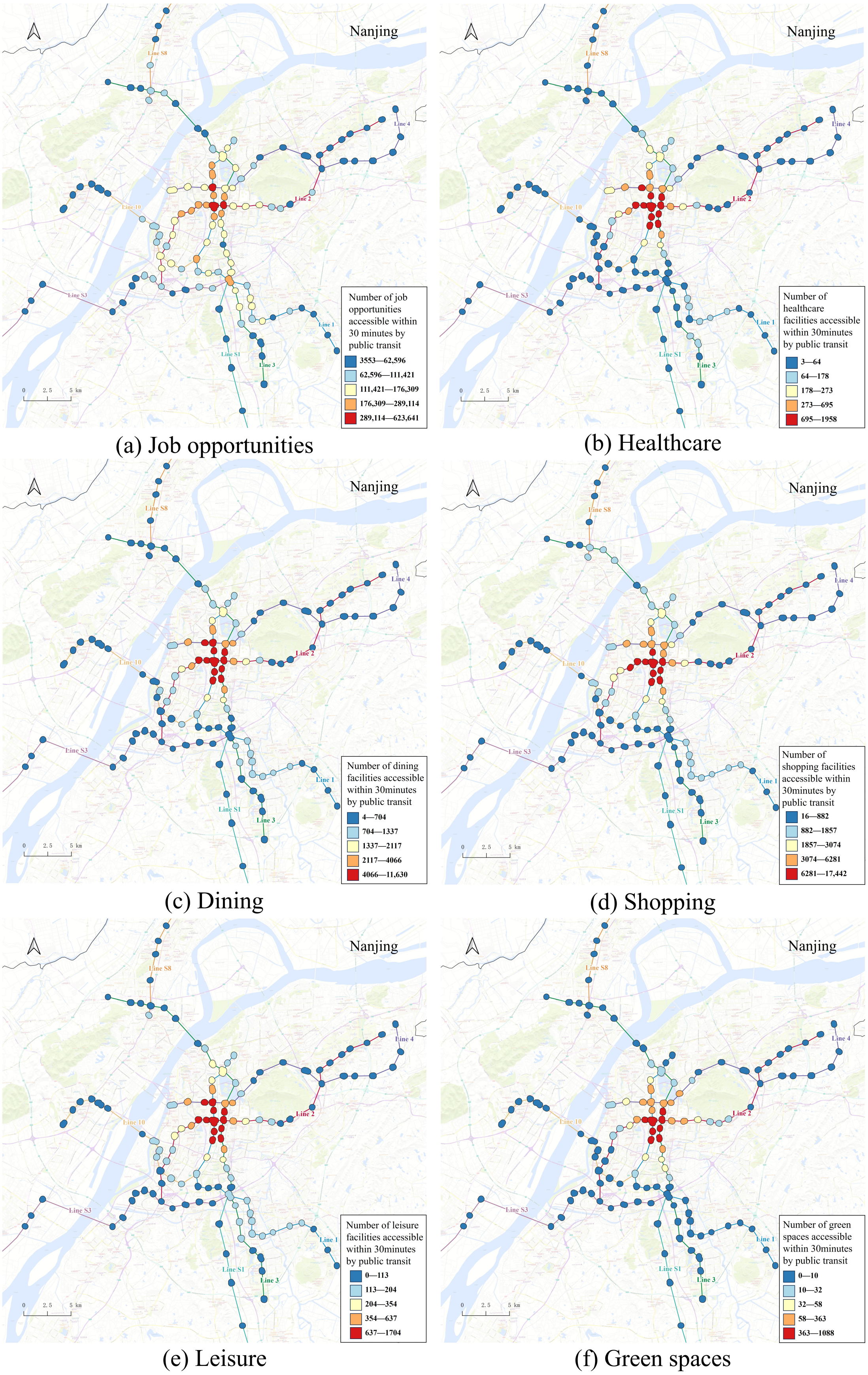



**Figure 6.** Spatial distribution of facility accessibility based on metro stations.

### 5.1.2. Effects of FFBS Integration on Public Transit Accessibility

This study focuses on FFBS integration as a first-mile/last-mile solution and its impact on public transit accessibility. As shown in Figure 7, replacing walking with FFBS—primarily cycling—significantly improves accessibility across the six analyzed travel destination types. This shift highlights the potential of micromobility to complement public transit systems, offering a flexible and efficient way to connect people to metro stations.

The results show that the improvement in accessibility varies across different destination types. Job opportunities benefit the most, with accessibility increasing by a remarkable 180.02%. This is likely because employment centers are concentrated in central areas, and enhanced first-mile connectivity improves access, allowing workers to reach job sites more quickly and affordably.

In contrast, healthcare facilities show the least significant improvement in accessibility, with a 108.09% increase. This is surprising, as healthcare facilities are generally expected to depend heavily on ease of access, particularly for vulnerable populations. However, the smaller improvement may reflect the more even spatial distribution of healthcare services across the urban area, which reduces reliance on central transit hubs compared to more concentrated land uses, such as employment and retail centers. Additionally, healthcare destinations may be less frequent or require specialized access that is less directly impacted by FFBS substitution.

Overall, the findings highlight the crucial role of first-mile improvements in enhancing the accessibility of public transit systems. Enhancing cycling infrastructure and integrating shared mobility options, such as bike-sharing, with public transit could promote more equitable and efficient transit services. These improvements are particularly vital for reaching underserved areas and optimizing access to key destinations, such as job centers, leisure spaces, and green areas.

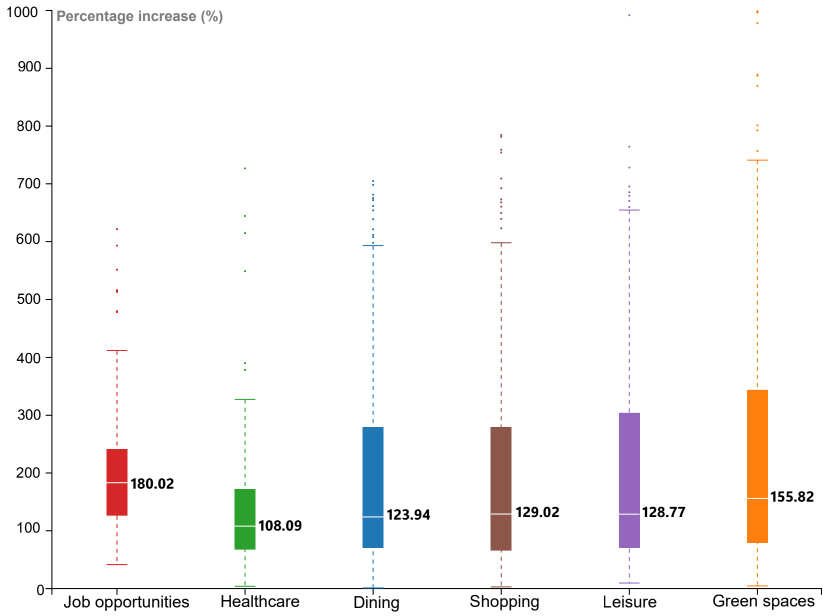



**Figure 7.** Comparison of accessibility improvement for six types of travel destination.

The percentage increase in accessibility across various travel destinations within public transit systems, shown in Figure 8, reveals distinct spatial distribution patterns. Stations that show the greatest improvement in accessibility are mainly located in outer residential areas, indicating that FFBS integration can significantly enhance public transit accessibility in suburban and peripheral zones. This spatial variation in accessibility improvements is more pronounced than the overall increase in accessibility, suggesting that the benefits of FFBS integration are not uniform across the city but are influenced by existing transportation infrastructure and the spatial distribution of facilities.

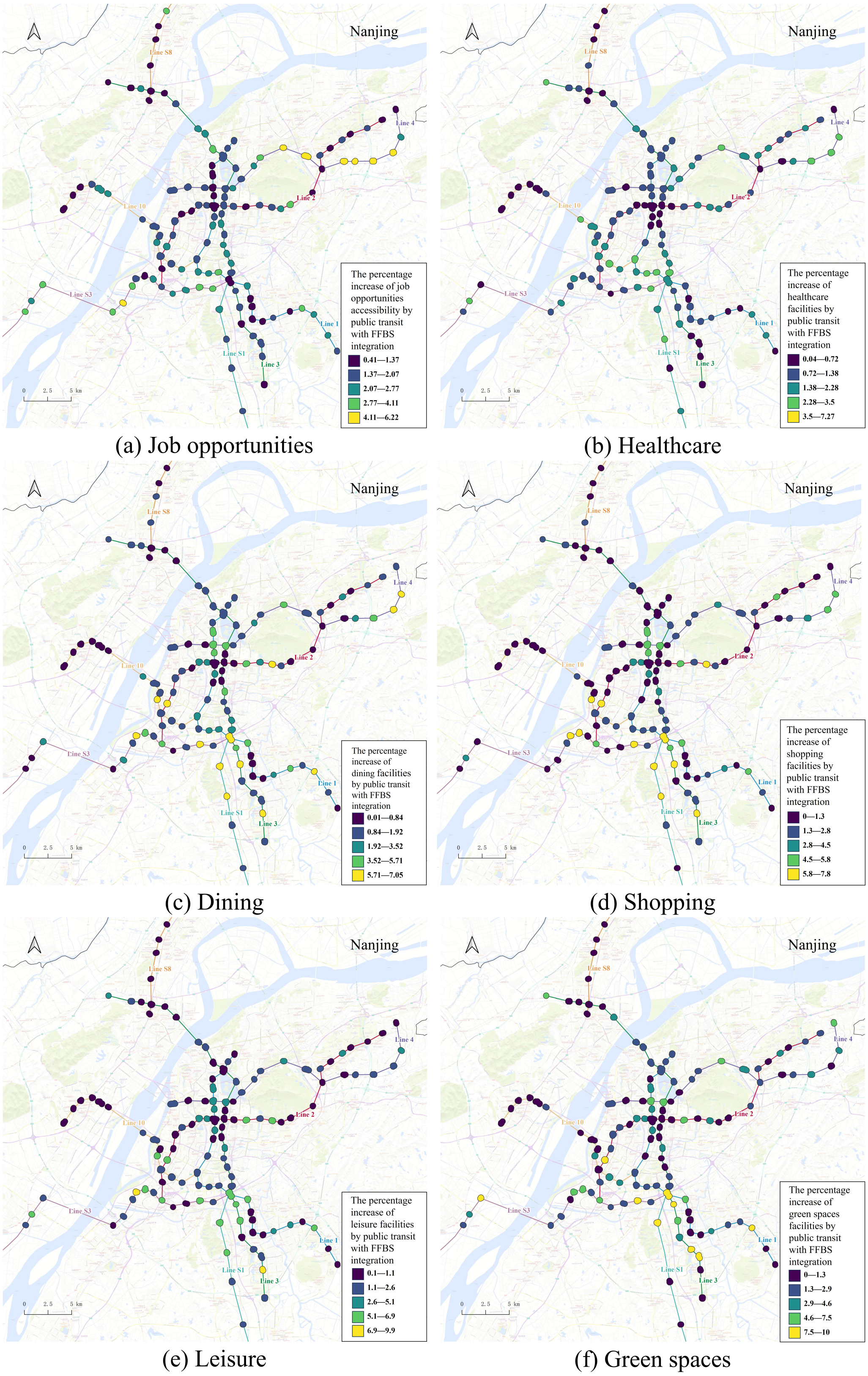



**Figure 8.** Spatial distribution of accessibility improvement by substituting walking with FFBS.

In terms of job opportunities, Figure 8a specifically highlights that the stations along Line S3 and the eastern section of Line 4 will experience significant improvements in accessibility for job opportunities through FFBS integration. These stations are likely situated in areas with high concentrations of employment, such as business districts and industrial zones, where enhancing accessibility could help alleviate commuting challenges. The substantial improvement in job accessibility indicates that integrating FFBS could particularly benefit workers in suburban areas who need more efficient connections to employment hubs in the city center. This finding has important implications for urban mobility policies aimed at improving commuter flow and supporting economic activity in both central and peripheral areas.

In terms of healthcare facilities, Figure 8b shows that the middle section of Line 4 and Line S1 stations will see substantial improvements in public transit accessibility for healthcare destinations. The accessibility boost in these areas is especially relevant for residents who may rely on public transit to access medical services. Healthcare facilities often serve a wide range of people, including those with limited mobility or lower incomes who might be dependent on public transportation. Enhancing accessibility to these destinations through FFBS could reduce travel time and improve health outcomes by making healthcare services more accessible to a broader segment of the population.

Figure 8c highlights significant improvements in accessibility for dining facilities, with stations along Line S1, the southern section of Line 3, the eastern section of Line 4, and the middle section of Line 2 showing marked increases. Dining facilities tend to be clustered in urban areas, especially around shopping districts, leisure zones, and transportation hubs. FFBS integration at these stations could further enhance accessibility to restaurants, cafes, and food courts, contributing to the vibrancy of these areas. This improved connectivity may also have economic benefits, as easier access to dining options could encourage consumer spending in the food and beverage sector.

For shopping facilities, Figure 8d indicates that the stations in the middle section of Line S3, middle section of Line 2, southern section of Line 3, and Line S1 will experience significant accessibility improvements. Shopping centers and retail outlets often attract large numbers of people, making accessibility a crucial factor for both consumers and retailers. The integration of FFBS in these areas will likely facilitate smoother and faster travel to popular shopping districts, enhancing the overall shopping experience and potentially boosting retail business. Additionally, improved access to shopping areas could help reduce congestion on main roads and in parking lots, encouraging sustainable transport choices.

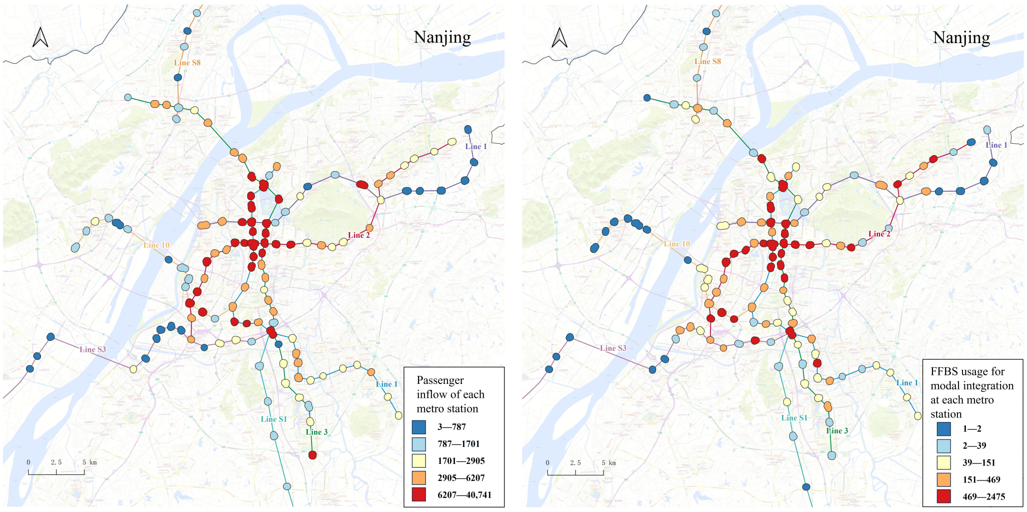
In terms of healthcare facilities, Figure 8e indicates that the integration of FFBS will significantly enhance public transit accessibility for leisure facilities, particularly through stations along the southern section of Line 3 and the middle section of Line S3. Leisure facilities, such as parks, entertainment venues, and cultural sites, are central to urban life and contribute greatly to residents' well-being and quality of life. These locations often attract diverse groups of people, ranging from tourists to local families, and their accessibility is key to promoting public engagement in recreational activities.

In terms of green spaces, Figure 8f shows that stations along Line S3, the southeast section of Line 3, Line S1, and the middle section of Line 1 will significantly enhance public transit accessibility to green spaces through the integration of FFBS. Green spaces, such as parks, gardens, and nature reserves, are essential for improving urban environmental quality and public health. The accessibility of these areas is especially important in densely populated cities, where the availability of open, green areas can provide crucial recreational and relaxation opportunities for residents.

### *5.2. Accessibility Equity of Public Transit Systems Across Different Areas*

#### 5.2.1. Spatial Characteristics of Passenger Trips and FFBS Usage

First, we explore the spatial distribution of passenger trips and FFBS usage, as depicted in Figure 9. Figure 9a highlights the daily passenger inflow at each metro station, while Figure 9b shows the spatial distribution of FFBS usage at these stations. The analysis reveals a clear spatial correlation between metro passenger inflows and FFBS usage, with both patterns exhibiting high accessibility in the city's central areas, which gradually declines towards the periphery. This trend is indicative of the concentration of key services, such as employment and retail, in the central business districts, as well as the higher availability of transportation options in these areas. The result further reinforces the idea that the integration of FFBS into the metro system could improve accessibility in less connected peripheral areas by facilitating seamless first-mile connectivity to metro stations.

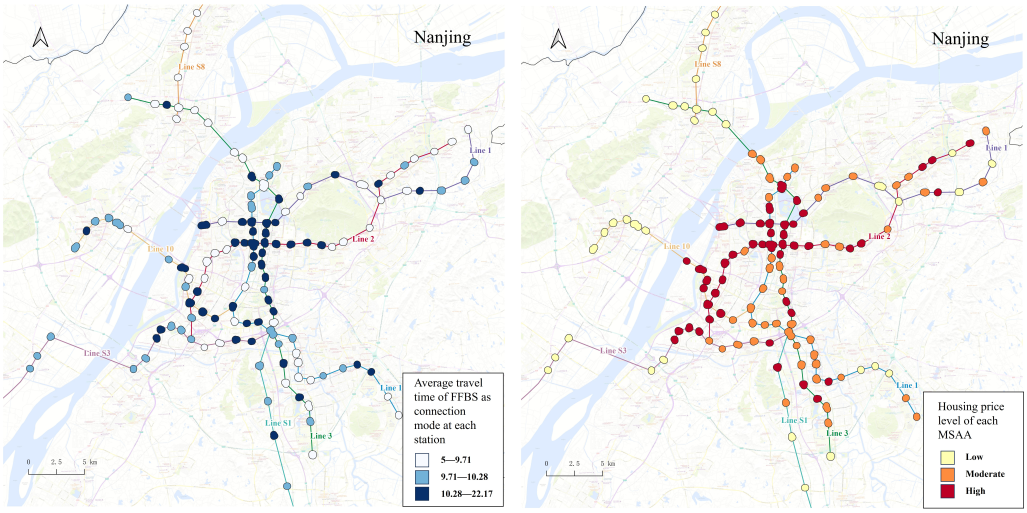



(a) Passenger inflow of metro station (b) FFBS usage for modal integration

**Figure 9.** Spatial distribution of trip volume based on metro stations.

### 5.2.2. Travel Time and Housing Prices

The integration of FFBS also influences travel time and housing prices across metro station areas. Figure 10a illustrates the average travel time of FFBS from each station, which serves as an indirect measure of the spatial extent of the affected Metro Station Affected Areas (MSAAs). Stations with longer travel times are generally associated with larger MSAA sizes, suggesting that FFBS has a greater impact on accessibility in more expansive suburban regions, where residential density is lower and transportation options are fewer.




(a) FFBS travel time at each station (b) Housing price level of each MSAA

**Figure 10.** FFBS travel time and housing price based on metro stations.

### 5.2.3. Accessibility Equity and the Role of FFBS

To analyze the impact of FFBS integration on accessibility equity, we employ the Lorenz curve and Gini coefficient methodology, as shown in Figure 11. The Lorenz curves depict the cumulative share of passenger inflow ordered by accessibility and the cumulative share of accessibility across different travel destinations.

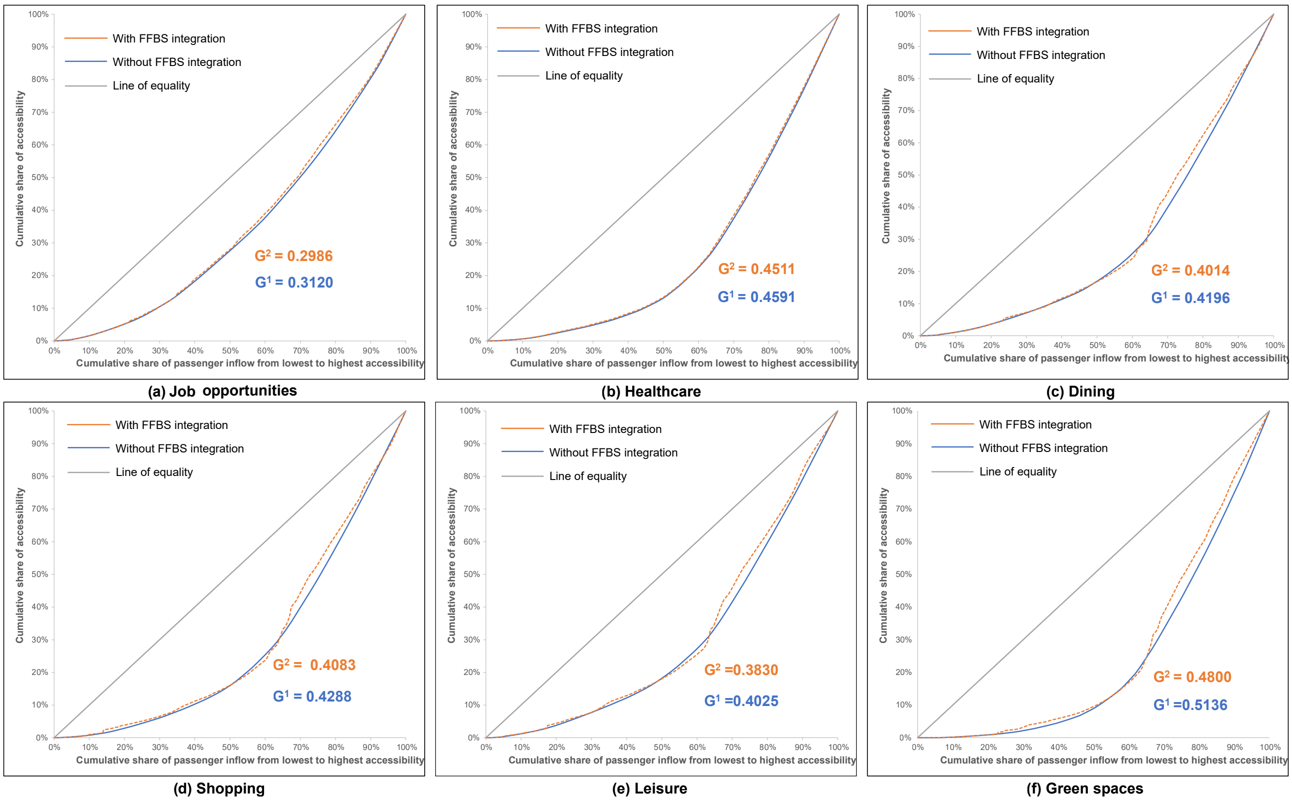



**Figure 11.** Lorenz curves based on accessibility for six types of travel destination.

Figure 11a demonstrates a notable improvement in accessibility equity for job opportunities after integrating FFBS into the public transit system. The Gini coefficient drops from $G^1 = 0.3120$ (without FFBS) to $G^2 = 0.2986$ (with FFBS), reflecting an improvement of $\Delta G = 0.0134$. This indicates that FFBS integration has a pronounced positive effect on making job opportunities more equally accessible across different metro stations. The improvement in equity is particularly significant given the central role that job accessibility plays in an individual's quality of life and economic well-being. In densely populated urban areas, where job centers are typically concentrated, FFBS can enhance access to these centers from peripheral residential areas, reducing spatial inequality in employment opportunities. This finding is particularly relevant for cities with large economic disparities or those with significant commuter populations from suburban areas. Integrating FFBS offers a way to bridge the accessibility gap by improving first-mile connectivity, making it easier for residents in outlying areas to efficiently reach key employment zones.

In Figure 11b, the Lorenz curve for healthcare facilities shows a relatively smaller improvement in accessibility equity after FFBS integration, with the Gini coefficient improving from 0.4591 to 0.4511, resulting in a modest $\Delta G = 0.008$. While this indicates a positive impact, the change is minimal. This could be due to the fact that healthcare facilities, particularly hospitals or medical centers, may already be relatively well-served by public transit networks, especially in urban centers. These facilities may not exhibit the same level of spatial inequality in accessibility as job opportunities, as healthcare services are often distributed more evenly across urban areas. However, even a small improvement in accessibility equity for healthcare facilities is noteworthy, especially in light of the importance of timely access to healthcare, particularly for vulnerable populations in peripheral or underserved areas. In these contexts, FFBS integration could help reduce delays and travel times, particularly for those living in residential areas further from medical centers.

As shown in Figure 11c, FFBS integration significantly improves accessibility equity for dining facilities, with a $\Delta G = 0.0182$ improvement, as the Gini coefficient decreases from 0.4191 to 0.4014. The accessibility of dining options is an important component of everyday urban life, and this result suggests that FFBS can make it easier for people in less accessible areas to reach restaurants, cafes, and other dining venues. Given the role of dining in both social interaction and economic activity, improving access to these facilities contributes not only to convenience but also to the social vitality of the city. This improvement may be particularly important in mixed-use neighborhoods, where both residential and commercial activities are concentrated but not necessarily well-connected by existing public transit infrastructure. FFBS integration could be especially beneficial in expanding access to dining facilities in the outer districts, which may be underserved by traditional public transportation options.

In Figure 11d, FFBS integration is shown to improve accessibility equity for shopping facilities, with a $\Delta G = 0.0205$ improvement, as the Gini coefficient decreases from 0.4083 to 0.4288. The positive impact on shopping facilities is likely due to FFBS facilitating easier access to commercial hubs and shopping districts, which are often located in central or high-density areas. This improvement underscores the potential of FFBS to support equitable access to essential retail services, especially for residents in suburban or peripheral areas, where access to shopping facilities might otherwise be more limited. Retail accessibility plays a key role in both economic vitality and social inclusion, as access to shopping areas is not only about consumer choice but also about opportunities for employment, services, and leisure activities. Improving this aspect of accessibility can help create more cohesive and connected urban areas, where all residents, regardless of location, can easily reach necessary commercial services.

As depicted in Figure 11e, FFBS integration significantly improves accessibility equity for leisure facilities, with a $\Delta G = 0.0195$ improvement, as the Gini coefficient decreases from 0.3830 to 0.4025. This result indicates that FFBS can help balance the access to recreational spaces such as parks, cultural institutions, and entertainment venues across different areas of the city. Access to leisure activities is a key factor in enhancing quality of life, and reducing inequality in this area can help ensure that all residents have the opportunity to engage in recreational and cultural activities. The improvement in equity for leisure facilities may be particularly relevant for areas where public transportation options are limited, and where residents in lower-income neighborhoods are at a disadvantage when trying to access parks, sports complexes, or community centers. By facilitating first-mile connectivity, FFBS can make these facilities more accessible, contributing to a healthier, more inclusive urban environment.

Figure 11f shows that FFBS integration provides the most substantial improvement in accessibility equity for green spaces, with the Gini coefficient improving from 0.4800 to 0.5136, resulting in $\Delta G = 0.0336$. This finding highlights that green spaces, which are crucial for environmental sustainability and public health, benefit significantly from the integration of FFBS. Access to parks, green corridors, and recreational areas is essential for fostering healthier communities, and improving access to these spaces helps reduce environmental and social inequalities in urban areas. Given the growing emphasis on urban green spaces for promoting public health, FFBS could play an important role in making these spaces more accessible, particularly for those living in neighborhoods that are further from such amenities. The improvement in equity suggests that FFBS has the potential to bridge the accessibility gap for underserved populations, enhancing the overall quality of life in cities.

#### 5.2.4. Housing Price Levels and FFBS Integration

To understand how FFBS integration impacts accessibility equity in areas with different housing price levels, this study examines the relationship between housing prices and the share of FFBS integration across various Metro Station Affected Area (MSAA) categories, as presented in Table 4. The results reveal notable spatial and socioeconomic trends that warrant further analysis.

**Table 4.** Share of FFBS integration across MSAAs with varying housing price levels.

| Housing Price Level | Metro Passenger Inflow (Person-Time) | FFBS Usage for Modal Integration (Person-Time) | Share of FFBS Integration (%) |
|---|---|---|---|
| Low | 61,159 | 985 | 1.61 |
| Moderate | 303,257 | 21,932 | 7.23 |
| High | 237,819 | 15,505 | 6.52 |
| Total | 602,235 | 38,422 | 6.38 |

1. MSAAs with moderate housing prices (7.23%)
   The highest share of FFBS integration is observed in MSAAs with moderate housing prices. This suggests that areas with moderate housing prices may have the most balanced distribution of infrastructure and services, making them prime candidates for the integration of alternative transport modes like FFBS. These areas likely represent neighborhoods where residents are both willing and able to adopt new modes of transportation, given that moderate housing prices often correlate with a broad demographic of residents who are not confined by extreme income constraints.
2. MSAAs with high housing prices (6.52%)
   MSAAs with high housing prices also exhibit substantial FFBS integration, although the share is slightly lower than in moderate-price areas. High-housing-price areas often have well-developed infrastructure and are home to more affluent residents. While FFBS integration may be less of a necessity for residents in these areas (who may have access to private vehicles or other transportation alternatives), it still plays a role in enhancing multimodal connectivity and environmental sustainability. This indicates that affluent areas are also adopting FFBS, likely due to the growing trend of eco-consciousness and the convenience of first-mile access.
3. MSAAs with low housing prices (1.61%)
   The lowest share of FFBS integration is found in low-housing-price MSAAs, where only 1.61% of residents benefit from the integration of bike-sharing with public transit. These areas, which typically correspond to lower-income neighborhoods, may face challenges such as limited access to infrastructure, lower public transport coverage, or less investment in sustainable mobility solutions. This stark contrast in FFBS integration suggests a need for targeted policy interventions to address the accessibility gap in these regions. The limited presence of FFBS integration in low-income areas may exacerbate existing transportation inequalities, as these areas may already struggle with poor connectivity and limited transportation options.

### *5.3. Accessibility Equity of Public Transit Systems in MSAAs with Different Housing Prices*

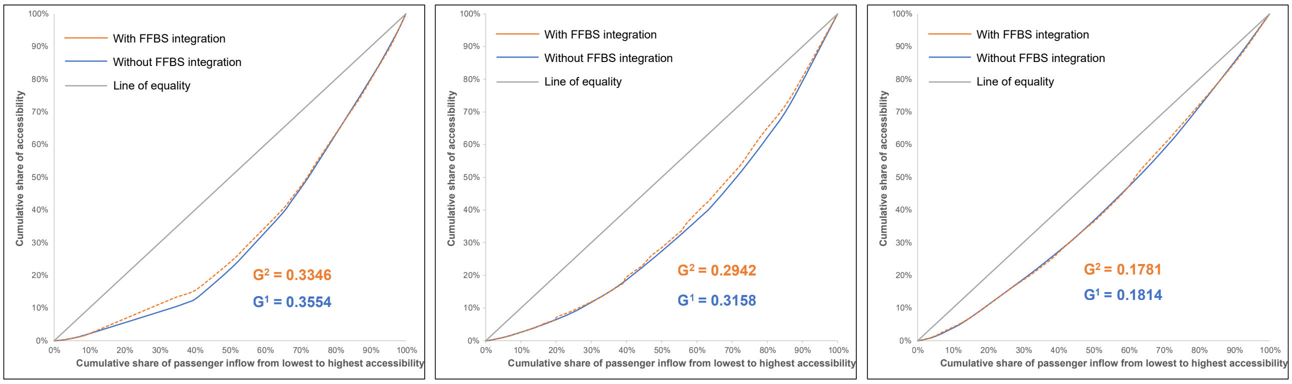
#### 5.3.1. Accessibility Equity for Job Opportunities

Figure 12 illustrates the Lorenz curves for MSAAs with varying housing price levels and their corresponding accessibility equity for job opportunities. The data analysis reveals a negative correlation between housing prices and the accessibility equity of the metro system: as housing prices decrease, the equity of access to job opportunities via the metro system deteriorates. This finding suggests that residents in lower-priced housing areas tend to face greater disparities in accessing job opportunities through public transit.

When examining the Lorenz curves without FFBS integration, the data reveals significant differences across housing price levels. For low-priced housing areas, the Lorenz curve is furthest from the equity line, with a Gini coefficient of $G^1_{low} = 0.3554$. This indicates that these areas experience the most significant inequities in terms of access to job opportunities. In contrast, moderate-priced areas show a more balanced distribution, with a Gini coefficient of $G^1_{moderate} = 0.3158$, suggesting relatively better access equity. High-priced areas, with a Gini coefficient of $G^1_{high} = 0.1814$, demonstrate the most equitable distribution of metro access to job opportunities, though still not perfectly aligned with the equity line.

Integrating FFBS into the public transit system shifts the Lorenz curves closer to the equity line for all housing price levels. The Gini coefficients with FFBS integration are $G^2_{low} = 0.3346$ for low-priced areas, $G^2_{moderate} = 0.2942$ for moderate-priced areas, and $G^2_{high} = 0.1781$ for high-priced areas. This shift indicates that FFBS integration improves accessibility equity across all areas, with the largest improvements occurring in low- and moderate-priced housing areas. For high-priced areas, the improvement is minimal, as these areas already exhibit relatively equitable access.

The improvements in accessibility equity, quantified by the change in Gini coefficient ($\Delta G$), vary by housing price levels. The greatest improvement is observed in moderate-housing-price areas, with a change of $\Delta G_{moderate} = 0.0216$. Low-housing price areas show a similar but slightly smaller improvement of $\Delta G_{low} = 0.0208$, while high-housing-price areas exhibit the smallest improvement of $\Delta G_{high} = 0.0033$. These results suggest that the integration of FFBS has the most pronounced positive effect in areas where accessibility equity is initially more unequal, particularly in moderate- and low-housing-price areas.




(a) Low housing price (b) Moderate housing price (c) High housing price

**Figure 12.** The Lorenz curves based on varying housing price levels and public transit accessibility for job opportunities.

5.3.2. Accessibility Equity for Healthcare Facilities

Figure 13 illustrates the Lorenz curves for MSAAs with varying housing price levels and their corresponding accessibility equity for healthcare facilities. The data reveal a clear trend in the relationship between housing prices and accessibility equity. MSAAs with high housing prices exhibit the highest accessibility equity in the public transit system, followed by those with low housing prices, and then those with moderate housing prices. This suggests that residents in high-priced-housing areas have relatively better access to healthcare facilities through the public transit system compared to residents in moderate- and low-priced areas.

The Lorenz curves without FFBS integration show a noticeable difference in accessibility equity across the different housing price levels. For low-priced-housing areas, the Gini coefficient is $G^1_{low} = 0.4455$, indicating relatively less equitable access to healthcare facilities. In contrast, the Lorenz curve for moderate-priced areas has a Gini coefficient of $G^1_{moderate} = 0.4789$, which suggests even greater inequality in access. High-priced areas, however, have the lowest Gini coefficient ($G^1_{high} = 0.3173$), showing the most equitable distribution of healthcare access among the three categories.

When FFBS integration is implemented, the Gini coefficients shift closer to the equity line across all housing price levels, suggesting a positive impact on accessibility equity. With FFBS integration, the Gini coefficients are $G^2_{low} = 0.4395$ for low-priced areas, $G^2_{moderate} = 0.4679$ for moderate-priced areas, and $G^2_{high} = 0.3092$ for high-priced areas. While the improvements are evident across all areas, the most substantial positive shifts occur in moderate- and low-housing-price areas. The integration of FFBS thus serves to reduce inequities in healthcare access, particularly in areas with less access to public transit.

The improvements in accessibility equity, quantified as the change in Gini coefficient ($\Delta G$), show that FFBS integration has the most significant effect on moderate-priced areas. The improvements in accessibility equity, ranked from highest to lowest, are as follows: $\Delta G_{moderate} = 0.011$, $\Delta G_{high} = 0.0081$, and $\Delta G_{low} = 0.0060$. These results demonstrate that the current FFBS deployment strategy is particularly beneficial for enhancing accessibility equity for healthcare facilities in moderate-priced MSAAs, likely due to the higher share of FFBS integration in these areas.

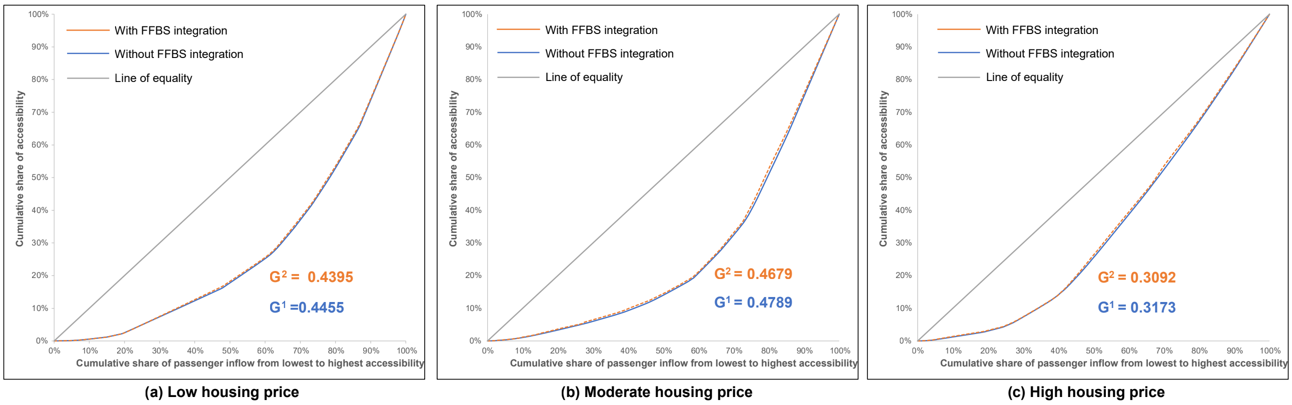



**Figure 13.** The Lorenz curves based on varying housing price levels and public transit accessibility for healthcare facilities.

5.3.3. Accessibility Equity for Dining Facilities

Figure 14 illustrates the Lorenz curves for MSAAs with varying housing price levels and their corresponding accessibility equity for dining facilities. The data reveal a distinct pattern in accessibility equity across different housing price categories. MSAAs with high housing prices exhibit the highest accessibility equity within the public transit system, followed by low-housing-price areas, and then moderate-housing-price areas. This suggests that residents in high-priced-housing areas have relatively better access to dining facilities through the public transit system, compared to those in lower-priced areas.

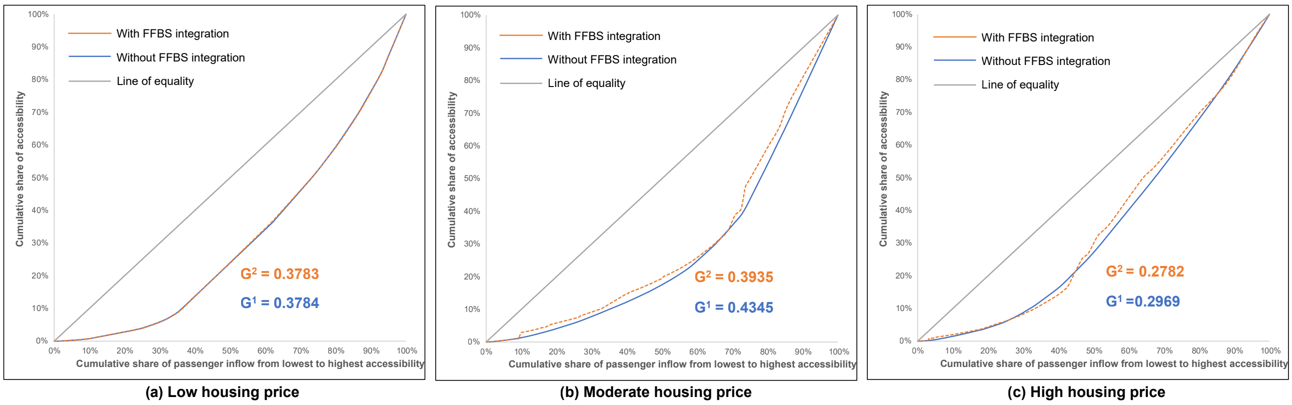



**Figure 14.** The Lorenz curves based on varying housing price levels and public transit accessibility for dining facilities.

When examining the Lorenz curves without FFBS integration, the Gini coefficients reflect the level of accessibility equity for dining facilities across the different housing price levels. The Gini coefficients for low-priced areas, moderate-priced areas, and high-priced areas are $G^1_{low} = 0.3784$, $G^1_{moderate} = 0.4195$, and $G^1_{high} = 0.2956$, respectively. This indicates that moderate-priced areas have the greatest inequality in dining facility accessibility, while high-priced areas have relatively more equitable access.

With FFBS integration, the Lorenz curves shift closer to the equity line, indicating improvements in accessibility equity for dining facilities. The Gini coefficients with FFBS integration are $G^2_{low} = 0.3783$, $G^2_{moderate} = 0.3833$, and $G^2_{high} = 0.2795$. The results suggest that FFBS integration has a positive effect on accessibility equity across all housing price levels, with the most notable improvements occurring in moderate-priced areas.

The improvements in accessibility equity, quantified by the change in the Gini coefficient ($\Delta G$), show a positive impact of FFBS integration. The improvements, ranked from highest to lowest, are as follows: $\Delta G_{moderate} = 0.0362$, $\Delta G_{high} = 0.0161$, and $\Delta G_{low} = 0.0001$. These findings indicate that the current FFBS deployment strategy is particularly beneficial for enhancing accessibility equity for dining facilities in moderate-priced MSAAs, largely due to the higher share of FFBS integration in these areas.

### 5.3.4. Accessibility Equity for Shopping Facilities

Figure 15 illustrates the Lorenz curves for MSAAs with varying housing price levels and the corresponding accessibility equity for shopping facilities. The data indicate that lower housing prices are associated with poorer accessibility equity in public transit systems for shopping facilities. This suggests that, in areas with lower housing prices, residents may have less equitable access to shopping destinations via public transit.

When comparing the Lorenz curves for MSAAs with FFBS integration and those without FFBS integration, the Gini coefficients reveal significant improvements in equity with FFBS integration. The Gini coefficients for the Lorenz curves without FFBS integration are $G^1_{low} = 0.4490$, $G^1_{moderate} = 0.4345$, and $G^1_{high} = 0.2969$. In contrast, the Gini coefficients with FFBS integration are $G^2_{low} = 0.4447$, $G^2_{moderate} = 0.3935$, and $G^2_{high} = 0.2782$. The curves with FFBS integration are closer to the equity line, indicating that FFBS integration improves accessibility equity for shopping facilities across all housing price levels.

The improvements in accessibility equity, quantified as changes in the Gini coefficient ($\Delta G$), are ranked from highest to lowest as follows: $\Delta G_{moderate} = 0.0410$, $\Delta G_{high} = 0.0187$, and $\Delta G_{low} = 0.0043$. These results demonstrate that FFBS integration most significantly enhances accessibility equity in moderate-priced MSAAs, where the most substantial improvement in the Gini coefficient is observed.

The findings suggest that the current FFBS deployment strategy is particularly effective in enhancing accessibility equity for shopping facilities in moderate-priced MSAAs, partly due to the highest share of FFBS integration in these areas. To improve accessibility equity further, increasing the share of FFBS (or other transportation mode) integration in low-priced MSAAs could be an effective strategy. By doing so, accessibility to shopping facilities could be improved in areas where the current equity gap is most prominent.

In conclusion, expanding FFBS integration in low-housing-price areas represents a promising strategy for improving accessibility equity and ensuring more equitable access to shopping facilities across all types of urban area.

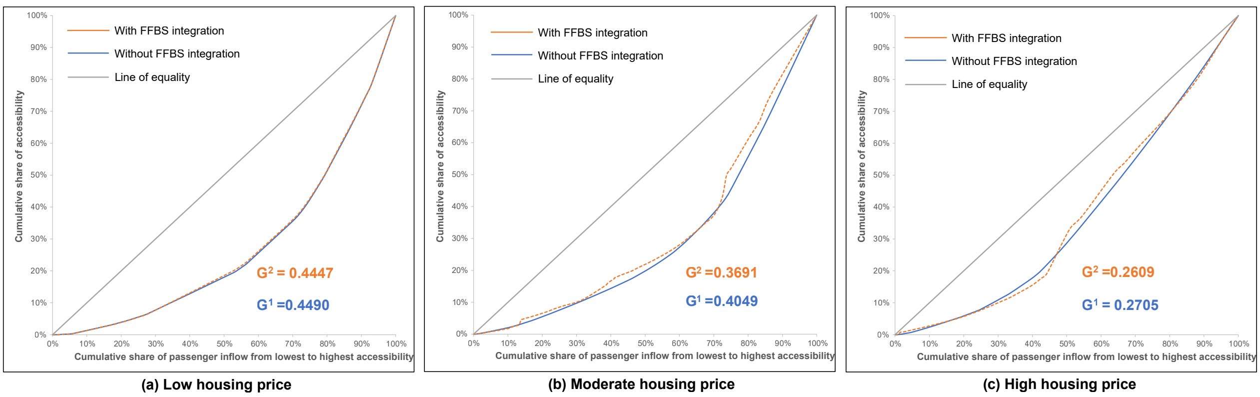



**Figure 15.** Lorenz curves based on varying housing price levels and public transit accessibility for shopping facilities.

### 5.3.5. Accessibility Equity for Leisure Facilities

Figure 16 presents the Lorenz curves for MSAAs with different housing price levels, illustrating the accessibility equity of public transit systems for leisure facilities. The data indicate that MSAAs with high housing prices demonstrate the highest accessibility equity, followed by those with low and moderate housing prices, respectively.

When comparing the Lorenz curves with and without FFBS integration, we observe notable differences in the Gini coefficients. Without FFBS integration, the Gini coefficients for the Lorenz curves are $G^1_{moderate} = 0.4049$ and $G^1_{high} = 0.2705$. In contrast, with FFBS integration, the Gini coefficients are $G^2_{moderate} = 0.3691$ and $G^2_{high} = 0.2609$. The curves with FFBS integration are closer to the equity line, indicating that FFBS integration enhances accessibility equity for leisure facilities in moderate and high-priced MSAA areas.

However, in MSAAs with low housing prices, the integration of FFBS appears to have a minimal effect on accessibility equity. Specifically, the Gini coefficients for low-priced MSAAs are as follows: $G^1_{low} = 0.3699$ without FFBS integration and $G^2_{low} = 0.3704$ with FFBS integration. The curve with FFBS integration is slightly farther from the equity line, indicating that FFBS integration does not improve accessibility equity in these areas. This contrast may be due to leisure facilities typically being located in suburban areas with low housing prices.

For moderate- and high-priced MSAAs, FFBS integration leads to significant improvements in accessibility equity, with the improvements ranked as follows: $\Delta G_{moderate} = 0.0358$ and $\Delta G_{high} = 0.0096$. These results suggest that FFBS integration has a notably positive impact on accessibility equity in moderate- and high-housing-price areas but is less effective in areas with low housing prices.

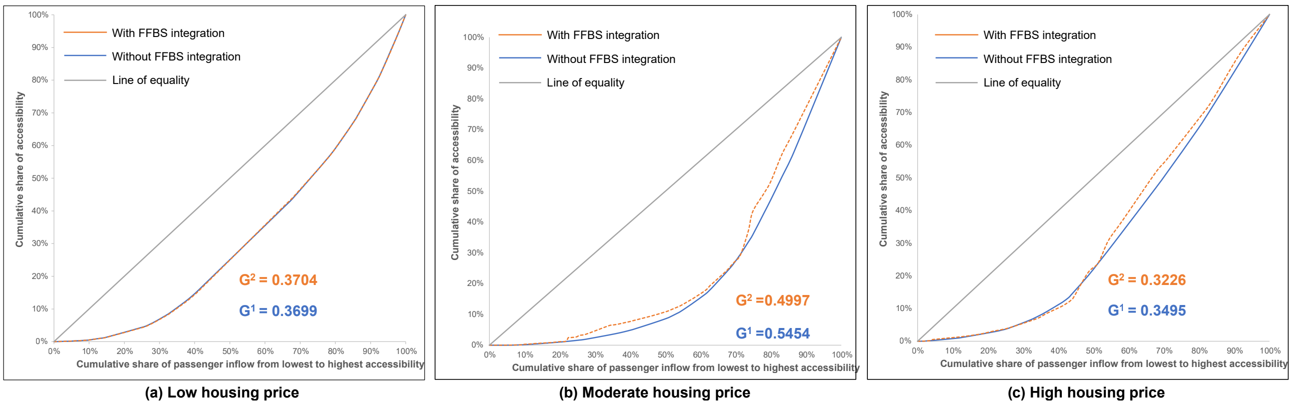



**Figure 16.** Lorenz curves based on varying housing price levels and public transit accessibility for leisure facilities.

### 5.3.6. Accessibility Equity for Green Spaces

The findings presented in Figure 17 reveal a notable relationship between housing price levels and the accessibility equity of metro systems, particularly in the context of green spaces. MSAAs with higher housing prices exhibit the highest accessibility equity, followed by areas with lower and moderate housing prices. This result aligns with the general expectation that wealthier areas, often characterized by better urban planning and infrastructure, tend to offer more equitable access to transportation networks. Higher housing prices are typically associated with better-maintained public services and infrastructure, including metro systems, which contribute to more balanced accessibility across different socio-economic groups.

When we examine the impact of FFBS integration on accessibility equity, a clearer picture emerges. Specifically, we observe that the Lorenz curves for MSAAs with high and moderate housing prices shift closer to the equity line after the integration of FFBS, with G-values improving from $G^1_{moderate} = 0.5454$ to $G^2_{moderate} = 0.4997$ and from $G^1_{high} = 0.3495$

to $G^2_{high} = 0.3226$. This shift indicates a significant enhancement in the accessibility equity of metro systems when FFBS is integrated into the transportation network. The inclusion of FFBS facilitates better first-mile and last-mile connectivity, improving access for underserved areas, which in turn leads to a more equitable distribution of public transit services across the urban population.

However, in MSAAs with low housing prices, the integration of FFBS appears to have an opposite effect on accessibility equity. Specifically, the Gini coefficients for low-priced MSAAs are as follows: $G^1_{low} = 0.3473$ without FFBS integration and $G^2_{low} = 0.3602$ with FFBS integration. The curve with FFBS integration is farther from the equity line, indicating that FFBS integration does not improve accessibility equity in these areas. This contrast may be due to green spaces typically being located in suburban areas with low housing prices, similar to leisure facilities.

Moreover, the improvements in accessibility equity for MSAAs with moderate and high housing prices ($\Delta G_{moderate} = 0.0457$ and $\Delta G_{high} = 0.0129$) are notable, but they underscore the need for a more targeted approach to bike-sharing deployment. It becomes clear that for FFBS to be truly effective in enhancing accessibility equity, it must be accompanied by a strategic and rational allocation of resources. This includes optimizing the distribution of bike-sharing stations to serve areas with high demand and low access to other forms of transportation. In particular, greater attention must be given to low-income MSAAs, where the barriers to accessibility are more complex and multifaceted.

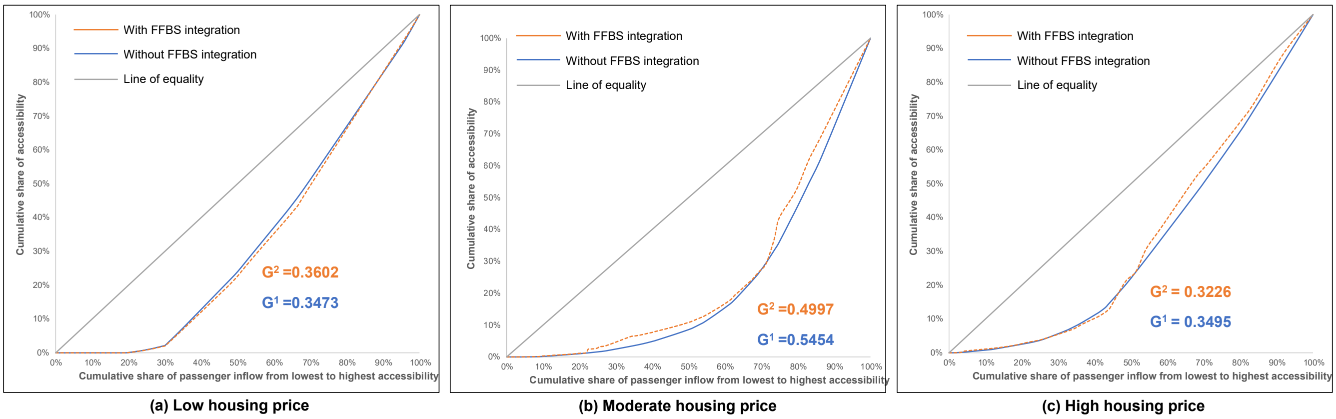



**Figure 17.** Lorenz curves based on varying housing price levels and public transit accessibility for green spaces.

### 5.4. Policy Implication

Based on the above results, several policy implications can be suggested:

1. Enhancing first/last-mile connectivity through FFBS integration

To enhance public transit accessibility, urban planners should prioritize integrating first-mile feeder bike-sharing systems with metro stations. Expanding bike-sharing infrastructure around metro stations, especially in underserved or low-accessibility areas, can reduce reliance on walking for first-mile trips, improve travel efficiency, and extend the reach of public transit services.

To achieve this, bike-sharing hubs should be established at key metro stations, particularly those with high commuter traffic, to improve first/last-mile connectivity. Additionally, bike-sharing fleets should be expanded in peripheral residential areas and underserved districts to ensure equitable access to metro services and reduce travel barriers for local residents.

2. Targeted improvements for underprivileged areas

Free-Floating Bike-Sharing (FFBS) systems have the potential to greatly improve accessibility in both urban centers and peripheral areas. Policymakers should ensure the inclusive deployment of FFBS, particularly in lower-income and suburban districts, where these systems can significantly connect residents to jobs, healthcare, and other essential services.

To achieve this, urban planners should focus on expanding FFBS coverage in suburban and low-income neighborhoods to address spatial inequalities in access to critical services, such as healthcare and employment. Additionally, subsidies or incentives should be provided to low-income residents to encourage the use of bike-sharing systems, helping to reduce transportation costs and barriers for underserved populations.

3. Increasing accessibility equity through resource allocation

Integrating FFBS enhances accessibility equity, particularly for essential facilities such as green spaces, healthcare centers, and shopping districts. Policymakers should ensure an equitable distribution of bike-sharing stations, addressing disparities across neighborhoods with different socioeconomic statuses, especially in areas with significant housing price variation.

To achieve this, urban planners should prioritize the equitable distribution of FFBS infrastructure across neighborhoods with varying housing prices, focusing on areas with the largest accessibility gaps (e.g., middle-income or low-income zones). Additionally, urban planners should ensure that high-demand areas, such as hospitals, business centers, and shopping hubs, are well-served by bike-sharing stations, balancing supply with demand.

4. Enhancing multi-modal transportation systems

To fully leverage FFBS as a first-mile solution, local governments should adopt policies that promote the seamless integration of various transportation modes, including metro, buses, and bike-sharing systems. This includes improving multi-modal facilities (e.g., bike racks at metro stations) and implementing technologies to facilitate smoother transitions between transport modes.

To achieve this, urban planners should invest in infrastructure, such as multi-modal hubs that integrate bus, metro, and bike-sharing stations, to simplify mode switching and enable seamless transfers. Additionally, urban planners should support the development of unified payment systems that allow users to pay for multiple transport modes (e.g., metro, bus, and bike-sharing) in a single transaction, improving convenience.

5. Monitoring and enhancing FFBS–metro integration

Continuous assessment is crucial to ensure that FFBS effectively enhances accessibility and equity. Policymakers should monitor usage patterns, equity impacts, and spatial disparities to adjust resource allocation and optimize bike-sharing station placement based on real-time data.

To achieve this, urban planners should conduct regular surveys and data collection to assess FFBS usage patterns, particularly regarding demographic accessibility and service equity. Additionally, urban planners should adjust the placement of bike-sharing stations based on real-time data to optimize service levels, particularly during peak commuting hours or as population demographics change.

6. Tailored policies for different socioeconomic areas

Residential areas, particularly those with differing housing prices, experience varying impacts from FFBS integration. Policymakers should customize bike-sharing deployment strategies to meet the specific needs of these areas, ensuring that FFBS benefits are distributed equitably across all socioeconomic groups, especially lower-income households.

To achieve this, urban planners should offer targeted subsidies or incentives to low-income residents to access bike-sharing systems and metro services, eliminating economic barriers to participation. Additionally, urban planners should improve bike-sharing availability in areas with lower housing prices, ensuring better access to essential services such as employment, healthcare, and shopping.

## 6. Conclusions

This study examines the impact of FFBS on the accessibility of public transit systems in Nanjing, focusing on its role as a first-mile feeder to metro stations. To achieve this, we integrate multi-source data, including job opportunities, housing prices, points of interest, and travel transactions from both metro and FFBS systems. This integration enables the evaluation of accessibility improvements resulting from FFBS–metro integration across six key services: job opportunities, healthcare, dining, shopping, leisure, and green spaces.

Accessibility is quantified based on the cumulative facility opportunities accessible within a 30-min travel time. We also examine changes in accessibility equity within public transit systems after FFBS integration, focusing specifically on Metro Station Affected Areas (MSAAs) across various housing price levels. The equity analysis provides quantitative insights into how FFBS, when used as a first-mile feeder, impacts accessibility equity. This study distinguishes itself from existing research by constructing a complete travel chain using real-world transaction data and route planning services, leading to more accurate and unbiased results. Furthermore, to the best of our knowledge, this is the first quantitative assessment of FFBS–metro integration aimed at evaluating accessibility equity across multiple opportunity categories.

The results show that replacing walking with FFBS for first-mile segments significantly improves travel efficiency. This improvement in efficiency leads to significant increases in the accessibility of public transit systems to six types of destinations: job opportunities (180.02%), green spaces (155.82%), shopping (129.02%), leisure (128.77%), dining (123.94%), and healthcare (108.09%). The distribution of these improvements shows spatial heterogeneity, with more pronounced gains and higher station concentrations observed in the central urban area and peripheral residential clusters. This suggests that facilities primarily accessed by public transit can benefit from targeted improvements to the cycling infrastructure. Consequently, this improvement boosts the competitiveness of the FFBS–metro integration strategy, significantly enhancing public transit's contribution to sustainable urban development.

The equity assessment results show that, without FFBS integration, the Gini coefficients for accessibility across various travel destinations are ranked from highest to lowest as follows: green spaces ($G^1 = 0.5136$), healthcare ($G^1 = 0.4591$), shopping ($G^1 = 0.4288$), dining ($G^1 = 0.4196$), leisure ($G^1 = 0.4025$), and job opportunities ($G^1 = 0.3120$). These rankings indicate an inequitable distribution of facility accessibility within the current public transit system. In contrast, FFBS integration improves accessibility equity, with the enhanced Gini coefficients ranked from highest to lowest as follows: green spaces ($G^2 = 0.4800$), healthcare ($G^2 = 0.4511$), shopping ($G^2 = 0.4083$), dining ($G^2 = 0.4014$), leisure ($G^2 = 0.3830$), and job opportunities ($G^2 = 0.2986$). The improvements in accessibility equity, ranked from greatest to least, are as follows: green spaces ($\Delta G = 0.0336$), shopping ($\Delta G = 0.0205$), leisure ($\Delta G = 0.0195$), dining ($\Delta G = 0.0182$), job opportunities ($\Delta G = 0.0134$), and healthcare ($\Delta G = 0.0080$). These findings suggest that FFBS integration significantly improves the accessibility equity of public transit systems across different opportunities.

This study evaluates the accessibility equity of public transit systems across MSAAs with different housing price levels. MSAAs with lower housing prices exhibit a more unequal distribution of access to job opportunities and shopping. In contrast, MSAAs with moderate housing prices show greater inequities in access to healthcare, dining, leisure, and green spaces. MSAAs with lower housing prices currently benefit less from FFBS integration, as these areas have the lowest share of FFBS integration. These areas, typically lower-income neighborhoods, may face challenges such as limited infrastructure, low public transport coverage, and insufficient investment in sustainable mobility solutions. The stark contrast in FFBS integration highlights the need for targeted policy interventions to address the accessibility gap in these areas. The limited presence of FFBS integration in low-income areas may worsen existing transportation inequalities, as these areas already face poor connectivity and limited transportation options. These findings suggest that the current FFBS deployment strategy is particularly effective in improving accessibility equity in MSAAs with moderate housing prices, particularly for job opportunities, healthcare, dining, and shopping facilities. Increasing FFBS integration (or similar modes) in MSAAs with lower housing prices would effectively enhance accessibility equity for these facilities. Additionally, the rational allocation and optimization of bike-sharing resources is crucial. For example, increasing the number of shared bicycles at metro stations with significant improvements in public transit accessibility would be beneficial.

This study has several limitations that should be acknowledged. First, the study constructs the public transit travel chain based on metro stations, excluding passengers who begin their trips elsewhere. Including these passengers in the model could improve result accuracy, highlighting the need for further research. Second, the study does not consider the monetary costs of FFBS usage, which may result in inaccurate estimates of accessibility and equity. A more accurate assessment could be achieved by considering both the travel time and monetary costs of FFBS usage simultaneously. Finally, future research could focus on a longitudinal approach to provide deeper insights into how the impacts of FFBS integration evolve over time, particularly regarding shifts in public attitudes and infrastructure adaptation.

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