

Article

Patterns and Synergistic Effects of Carbon Emissions Reduction from Shared Bicycles in the Central Urban District of Nanjing

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Abstract

With accelerated urbanization and the pursuit of the “dual carbon” goals, shared bicycles have re-emerged as a green travel option. This study focuses on the central urban area of Nanjing and develops a carbon emissions reduction (CER) estimation model for shared bicycles. By analyzing spatio-temporal dimensions, it systematically assesses carbon reduction benefits and highlights the synergy with metro-connected travel. Key findings are as follows: (1) shared bicycles primarily support short-distance commuting, with a daily cycling pattern exhibiting a bi-modal distribution and a pronounced peak period demand; (2) cycling trips concentrate in densely populated and commercially vibrant zones, with a spatial pattern of central aggregation and multi-point diffusion; (3) each kilometer cycled by a shared bicycle reduces carbon emissions by about 96.19 g, with daily reductions of around 42.72 t and annual reductions up to 15,591.04 t; (4) the CER benefits of bicycle–metro integration are especially pronounced, contributing nearly 45.00% during peak periods; and (5) factors such as travel mode shifts, metro station layouts, and the development of electric vehicles continue to influence the CER benefits of shared bicycles. This work provides scientific evidence to inform urban green travel policies and transportation infrastructure optimization in cities.

Keywords: shared bicycles; carbon emissions reduction; bicycle–metro integration; spatio-temporal pattern; green travel; Nanjing



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1. Introduction

With the continued progression of urbanization and increasing travel demand among residents, energy consumption and carbon emissions in urban transportation have become one of the key challenges to achieving China’s “dual-carbon” goals. In 2020, China set the target of peaking carbon emissions before 2030 and achieving carbon neutrality before 2060, with transportation identified as a key area for emission reductions.

Thus, green and low-carbon travel was made a cornerstone of urban sustainable development [1]. In this context, micro-mobility modes represented by shared bicycles have rapidly diffused across cities owing to their convenience and flexibility, representing a pivotal solution to the first-mile/last-mile problem and contributing positively to alleviating

traffic congestion and improving air quality [2]. In addition to reducing carbon emissions, shared bicycles can also significantly lower the environmental noise associated with traffic, yielding synergistic benefits for urban livability [3]. In recent years, shared bicycles have developed rapidly in China. Statistics indicate that shared bicycles have become an important supplementary mode of short-distance travel for urban residents, with daily travel volumes in some large cities accounting for about 5% of total transportation trips [4]. At the same time, the impact of shared bicycles is expanding globally, with rapid promotion and adoption observed in Europe, the Americas, and Southeast Asia [5]. Against the backdrop of rising motor vehicle ownership and mounting transportation emission pressures, systematically quantifying and evaluating the carbon reduction benefits of shared bicycles not only help to reveal their spatio-temporal mechanisms within cities but also provides empirical evidence and methodological references for green transportation policies on a global scale.

In recent years, the spatial-temporal patterns of urban transport emissions have attracted substantial attention. Research indicates that transport carbon emissions tend to display a center-periphery (or center-radiation) spatial pattern, with higher intensities in core urban areas and relatively lower levels in peripheral regions; temporally, they exhibit a pronounced peak-valley effect, with emissions concentrated during peak periods of intense traffic activity [6,7]. As urban rail transit systems are progressively improved and green travel options are promoted, understanding the spatio-temporal evolution of transport emissions has become a fundamental basis for optimizing transport structures and formulating low-carbon policies [8].

Regarding the carbon reduction benefits of shared bicycles, the literature focuses on three aspects: (i) methods for estimating carbon reductions, where researchers typically employ travel substitution models or carbon-emission factor estimation to quantify emissions avoided when shared bicycles replace other modes [9–11]; (ii) evaluation of reduction effects, examining how benefits vary across cities, regions, and time scales [12–14]; and (iii) identification and quantification of influential factors, exploring how urban form, travel characteristics, and policy interventions constrain carbon reduction capacity [15–17]. For example, Zhang et al. [18] used big data to estimate shared-bicycle carbon reductions and revealed temporal variations; Kou et al. [19] constructed a carbon reduction estimation model and compared reductions across eight cities; Li et al. [20] developed travel-mode substitution models to assess shifts in travel behavior; Chen et al. [21] analyzed environmental benefits and their spatio-temporal distribution in New York City from 2014 to 2017; Cao et al. [22] conducted qualitative and quantitative analyses to examine factors affecting Beijing's shared-bicycle carbon reductions; Zhang et al. [23] compared reduction potential across cities at different development stages. Concurrently, recent work has begun to examine the synergy between shared bicycles and other public transport modes, particularly the inter-modal use with rail systems, which can amplify the overall carbon reduction benefits of the transport system [24]. Some studies indicate that the “shared bicycle + metro” paradigm not only enhances commuting efficiency but also markedly intensifies the transport system's carbon reduction effects, offering new avenues to mitigate congestion on urban arterials and to optimize green transport structures [25–28]. However, most studies do not adequately account for the spatio-temporal heterogeneity of shared-bicycle usage, hindering fine-grained characterization of reductions during peak periods and within micro-spatial units; likewise, research on the co-reduction mechanisms between shared bicycles and metro or other public transport remains in early stages, with relatively few city-specific quantitative analyses.

This paper constructs a carbon reduction estimation model for shared bicycles, systematically analyzes reduction benefits and their spatio-temporal distribution under different

scenarios, and emphasizes the carbon reduction role of metro-connected travel. The aim is to provide theoretical and practical guidance for formulating urban green-travel policies and optimizing transport structures. This article aims to analyze the magnitude of shared bicycles' impact on carbon reduction, and to examine the differences in carbon reduction benefits of shared bicycles under scenarios of transitions between different travel modes. Given Nanjing's recent strong emphasis on building a green travel system, with ongoing expansion of shared bicycles, optimization of public transit, and development of walking and cycling networks, the city's low-carbon transportation system is increasingly well developed. Since the central urban district of Nanjing experiences the highest frequency of shared-bicycle usage, robust cycling demand, and substantial inter-modal connections, it provides a solid empirical basis and substantial carbon reduction potential for the study. Accordingly, this study selects Nanjing's central urban district as the study area for empirical analysis. The innovations of this study are twofold. Methodologically, it develops a carbon reduction estimation model for shared bicycles and employs a range of analytical approaches to reveal spatio-temporal features from multiple perspectives. In terms of policy implications, it not only concentrates on the local practice in Nanjing but also offers references and decision-support for green transportation transitions in other regions.

2. Materials and Methods

This study focuses on Nanjing's central urban district as the study area and assesses carbon reduction benefits by estimating the carbon reductions from shared bicycles. The research comprises four steps (Figure 1): first, screening and cleaning the shared-bicycle trip data, and systematically analyzing the spatio-temporal characteristics and dynamics of bicycle usage in the central district; second, integrating carbon reduction factors associated with different travel modes to compute the carbon reductions attributable to the central district's shared bicycles, and evaluating the scale of reductions under a metro-connecting scenario, followed by a spatial analysis of the results; third, performing a sensitivity analysis of the carbon reduction benefits to examine how changes in travel modes, the development level of metro stations, and the diffusion of electric vehicles influence the estimated reductions; fourth, synthesizing the findings to discuss policy implications and study limitations.

2.1. Study Area

Nanjing is located in Eastern China, in the lower Yangtze River region. It is the capital city of Jiangsu Province and one of the major cities along China's eastern coastal area. Over the past two decades, the total travel demand of residents in Nanjing has grown significantly, while road infrastructure has been continuously improved and public transport has undergone rapid development. This study selects the central urban district of Nanjing as the study area (Figure 2). The central urban district covers a total area of 243.67 km² and includes the six districts of Xuanwu, Qinhuai, Jianye, Gulou, Yuhuatai, and Qixia. Although the central district accounts for only 3.7% of the city's total area, it houses nearly 3 million permanent residents and serves as the political, economic, cultural, and transportation hub of Nanjing, with well-developed infrastructure and relatively high population density.

The central urban district of Nanjing is also the core operating region for shared bicycles, with coverage by all three major brands. The usage of shared bicycles in the central district accounts for approximately 70% of the city's total, and its carbon reduction effects reflect, to some extent, the overall carbon reductions achieved by shared bicycles in Nanjing. To further analyze travel modes and carbon reduction effects of shared bicycles, this study employs hexagonal grid tessellation to partition the study area. Compared with

traditional square grids, hexagonal grids offer advantages such as boundary balance and stronger directional consistency, enabling a more accurate reflection of the continuity of spatial phenomena. On this basis, balancing spatial precision and data density, the study partitions the area using hexagons with a side length of 200 m, yielding a total of 2452 grids. This grid system effectively expresses the spatial characteristics of shared-bicycle usage while mitigating sample sparsity that may arise from overly small grids.

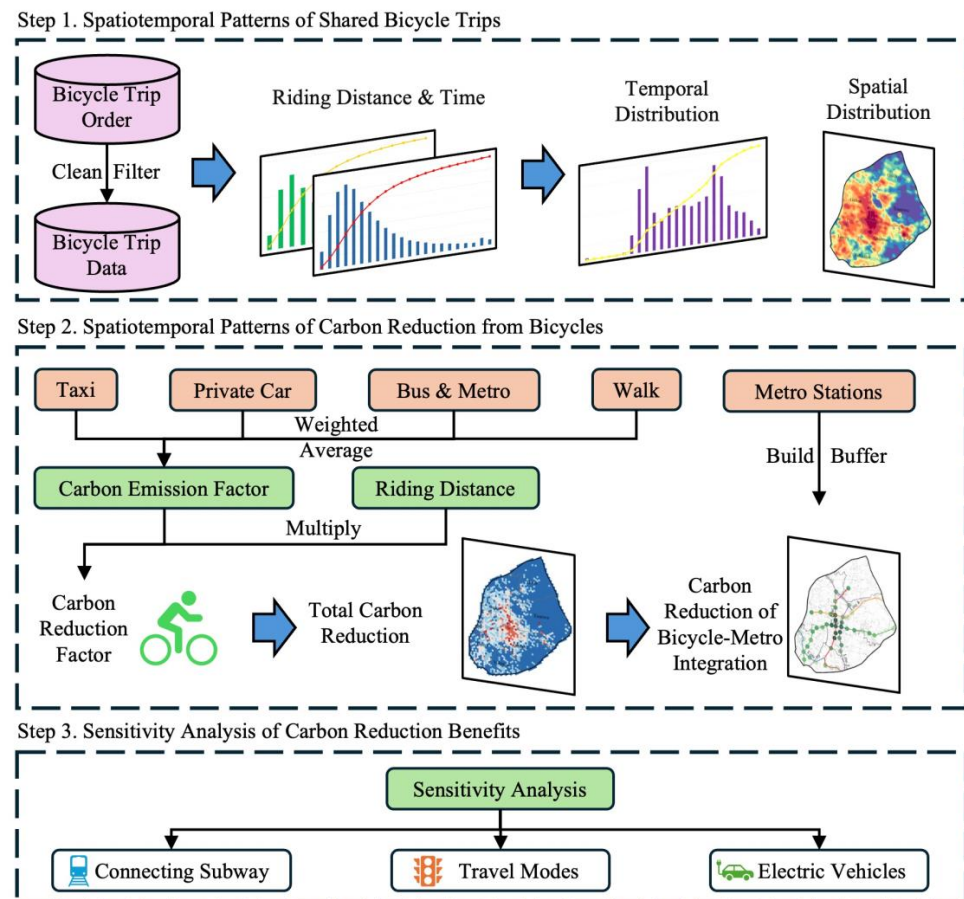


Figure 1. Research framework.

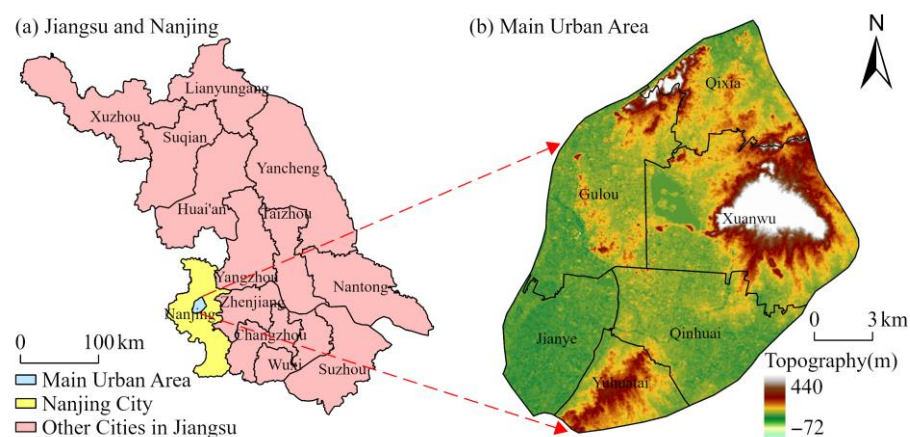


Figure 2. Study area: (a) Jiangsu province; (b) main urban area.

2.2. Data

This study utilizes four types of data: shared-bicycle trip data, metro station data, socio-economic data, and administrative boundary data. The shared-bicycle trip data were

derived from the order records from 12–18 October 2018 in Nanjing, including attributes such as order date, trip coordinates, and trip duration (see Table 1). In that time period, the weather in Nanjing was overcast, with temperatures ranging between 10 °C and 20 °C, and the overall environment was suitable for cycling. After data cleaning and processing, 2,845,353 valid records were retained. Metro station data were obtained via the Amap (Gaode) Open Platform API, covering five metro lines and sixty-five stations. Socio-economic data were sourced from the Nanjing Bureau of Statistics, and administrative boundary data were from the National Geospatial-Data Center of China (NGCC).

Table 1. Examples of shared bicycle trip data.

Trip number	Bicycle number	Bicycle brand	Trip date
153932032473	7310167786	Hellobike	12 October 2018
864001236215	8640012362	Mobike	12 October 2018
Start time	End time	Start coordinates	End coordinates
12:45:00	12:58:37	118.8543, 32.0531	118.8391, 32.0380
12:50:03	12:58:50	118.8118, 32.0574	118.8077, 32.0527

This study conducts systematic screening and cleaning of the shared-bicycle trip data to ensure the reliability of the results. Based on the attributes of the shared-bicycle trips, riding distance and riding time can be computed. Some records exhibit abnormal values (too short or too long) for distance or time, which may be due to malfunctions such as rider-reported scooter faults after unlocking (leading to shorter travel distances) or GPS/lock-system errors causing inflated distance or time calculations. To exclude invalid observations, records with a riding distance below 100 m or above 5 km, and a riding time below 30 s or above 30 min were removed. Subsequently, spatial clipping was performed using the boundary data for Nanjing’s central urban area, resulting in 2,845,353 trips within the central city.

2.3. Research Method

2.3.1. Estimation Model for Carbon Emissions Reduction

Shared bicycles, as a green mode of transportation, play an important role in reducing greenhouse gas emissions [29]. To quantify their carbon reduction effects, this study, drawing on related research [30,31], adopts the following formulas to estimate carbon reductions:

$$C = D \times E_b \quad (1)$$

$$E_b = \sum O_i \times e_i \quad (2)$$

where C denotes the total carbon reductions from shared bicycles. D represents the total riding distance of shared bicycles; and in this study, the Manhattan distance between the trip origin and destination is used as an approximation of the cycling distance. E_b denotes the carbon reduction factor of shared bicycles, which is the weighted average per-person-per-kilometer carbon emissions of the various travel modes that shared bicycles substitute. O_i represents the share of each travel mode among all travel modes, and e_i denotes the per-kilometer carbon emissions of each travel mode. Manhattan distance, though a simplified estimate of actual cycling routes, can reasonably approximate cycling distances within a city’s grid layout, and thus remains a valid proxy for analyzing total carbon reductions. Regarding travel substitution, this study posits that shared bicycle trips with a cycling distance of up to 1 km primarily substitute walking, while trips longer than 1 km substitute other modes of transportation. Walking is typically the preferred mode for trips within a 1 km range, accordingly [32]. Since walking does not generate additional

carbon emissions, the carbon reductions from substituting walking with shared bicycles are considered zero [33–35]. For trips longer than 1 km, people typically choose multiple modes such as public transport (bus, metro), taxis, private cars, motorcycles, electric bicycles, bicycles, etc. Because some travel modes have low shares and data on public transport usage is difficult to obtain, this study omits these other modes in the calculation and mainly considers the carbon-emission factors of private cars and taxis.

(1) Carbon-emission factors of private cars

In previous studies, private cars have typically been treated as internal-combustion-engine vehicles. However, with the rising penetration of electric vehicles in recent years, this study incorporates electric vehicle factors into the carbon-emission factors to obtain more realistic estimates. Moreover, since the carbon-emission factors must be computed on a per-person basis, the model also accounts for the number of occupants per vehicle, i.e., the seating capacity. Accordingly, the calculation is performed on a per-passenger basis, with appropriate weighting to reflect occupancy. The specific implementation is as follows:

$$e_c = (CI_g \times P_g + CI_e \times P_e) / L \quad (3)$$

where e_c represents the average carbon-emission factor for private cars, which corresponds to the shares and per-type emission factors of internal-combustion-engine (ICE) vehicles and electric vehicles (EVs). Specifically, P_g denotes the share of ICE vehicles in total travel, and P_e denotes the share of EVs in total travel. L represents the load factor of the vehicle, i.e., the number of passengers relative to seating capacity, which is used to weigh emissions on a per-passenger basis. The value of L in this study is derived from the traffic travel statistics of Nanjing.

(2) Carbon-emission factors of taxis

Similar to private cars, the taxi carbon-emission factor should also account for the share of electric vehicles. However, in 2018, taxis in Nanjing were predominantly internal-combustion-engine vehicles, with a relatively low penetration of electric vehicles. The specific calculation formula is as follows:

$$e_t = ((CI_g \times P_g + CI_e \times P_e) \times A \times N) / (P \times d_t) \quad (4)$$

where e_t represents the average carbon-emission factor for taxis; A represents the annual average distance traveled per taxi; N represents the total number of taxis in the city; P represents the annual passenger traffic of taxis in the city; and d_t represents the average driving distance per passenger riding a taxi.

2.3.2. Kernel Density Estimation Model

Kernel density estimation is a common nonparametric spatial analysis method used to estimate the spatial distribution density of point features, providing an intuitive reflection of the degree of clustering and spatial distribution characteristics of point features [36]. Kernel density estimation calculates the influence of each point feature on its surrounding area by placing a kernel function and a search radius around the point, thereby producing a continuous density surface. Higher density values indicate a denser distribution of point features in that area. This study adopts kernel density estimation to analyze the spatial clustering characteristics of shared-bicycle riding trips in the core urban area of Nanjing. Bandwidth selection is performed using a plug-in method to balance the smoothness of the

kernel density estimate and the data fitting performance. The corresponding formula is as follows:

$$f(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - X_i}{h}\right) \quad (5)$$

where $f(x)$ represents the kernel density function at a given location in space x ; n is the total number of shared-bicycle trip start and end points; h is the bandwidth; K is the spatial weighting function; and $x - X_i$ is the distance from the observation point to the sample point.

2.3.3. Buffer Analysis

Buffer analysis is a commonly used technique in spatial analysis, which creates buffer zones around a point, line, or polygon features at a specified distance to identify the extent of influence or to evaluate potential effects within a designated area. Buffers can be single buffers or multi-ring buffers. This study employs a multi-ring buffer approach to analyze the usage of shared bicycles within different radius ranges around metro stations, and to further estimate the carbon reductions from shared bicycles that dock with the metro. Figure 3 illustrates the concept of constructing multi-ring buffers around point features.

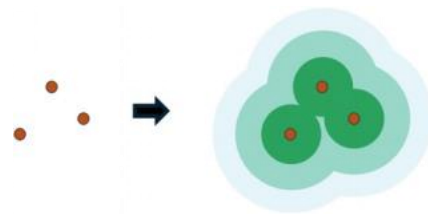


Figure 3. Three-Level Multi-Ring Buffers around Vector Points.

3. Results

3.1. Spatial and Temporal Patterns of Shared-Bicycle Travel

3.1.1. Travel Distance and Travel Time

Travel distance and travel time are key indicators for characterizing the overall features of shared-bicycle travel. In the core urban area of Nanjing, the average travel distance and average travel time for shared bicycles are 1287.21 m and 8.70 min, respectively, indicating that shared bicycles are predominantly used for short trips. As shown in Figure 4, approximately 34.88% of trips have distances between 600 m and 1200 m, and more than 72.79% of trips are shorter than 1600 m. This suggests that the deployment of shared bicycles significantly enhances daily short-distance mobility, effectively fills the transportation gap for urban short trips, and plays an important role in addressing the “first mile” and “last mile” challenges.

Compared with travel distance, the distribution of travel time exhibits more pronounced characteristics, clearly highlighting the advantage of shared bicycles for short-distance trips. As shown in Figure 5, about 65.00% of travel times fall within 2 to 10 min; when travel time exceeds 10 min, the number of trips declines rapidly, and 87.72% of travel times do not exceed 16 min, indicating that users tend to choose faster modes of transport for longer distances. In contrast, trips with travel times below 2 min account for less than 5.00%, suggesting that when the destination is close, the frequency of shared-bicycle use is relatively low and its advantage is less apparent. Overall, in scenarios characterized by long walking times, moderate cycling times, and high driving costs, shared bicycles become the preferred option due to their low cost, high flexibility, and convenience. Shared bicycles can help users reach destinations quickly in a short time, thereby highlighting their unique value as a tool for short-distance travel.

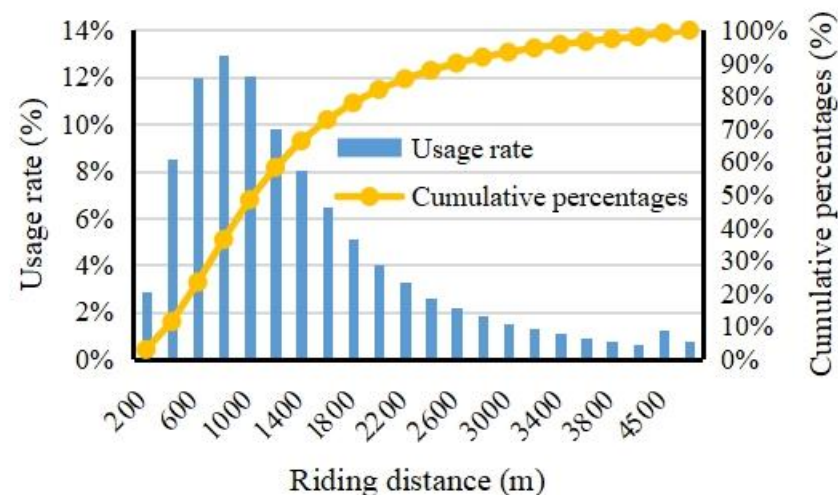


Figure 4. Riding distance for bicycle trips.

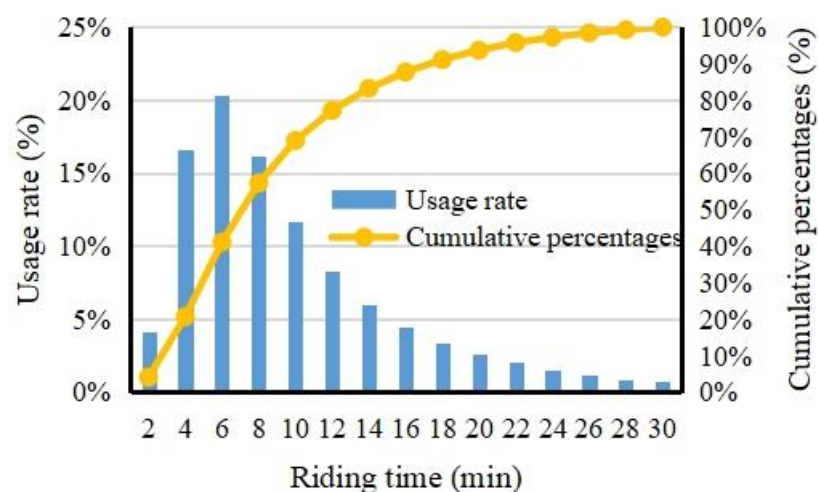


Figure 5. Riding time for bicycle trips.

3.1.2. Temporal Distribution of Bicycle Trips

This study orders cycling trips chronologically, analyzes the start times of cycling trips, and presents the temporal distribution of shared-bicycle trips (Figure 6). The temporal distribution shows that demand for shared bicycles follows a typical bi-modal distribution over a 24 h day, reflecting pronounced peaks and troughs. There are two obvious peak periods: the morning peak from 7:00 to 9:00 and the evening peak from 17:00 to 19:00. This indicates that shared bicycles are widely used as a commuting mode during peak hours. However, the characteristics of these two peaks differ.

During the morning peak, usage rises rapidly from 7:00, with the number of trips from 7:00 to 8:00 being 3.44 times that of the previous hour. Subsequently, the peak occurs from 8:00 to 9:00, with trip counts reaching 51,160. After 9:00, the morning peak declines quickly, with trips from 9:00 to 10:00 dropping by 55.65% compared with the previous hour. This pattern is closely related to the concentration and time-urgency of commuting demand in the morning, as most users need to reach workplaces before 9:00, resulting in a shorter peak duration but a higher peak magnitude.

In contrast, the evening peak is more gradual in its dynamics. Although the total number of trips during the evening peak is slightly lower than that of the morning peak (by 5063 trips), the rate of increase and decrease during the evening period is slower. Trips from 16:00 to 17:00 and 19:00 to 20:00 account for 57.01% of the total evening-peak trips, indicating that evening demand is dispersed over a longer time window. This may relate

to diversified nighttime lifestyles, especially among young people who favor nighttime entertainment and leisure activities rather than returning home immediately. Additionally, different industry-specific after-work times (e.g., the internet sector often closes later than traditional industries) can prolong the duration of the evening peak.

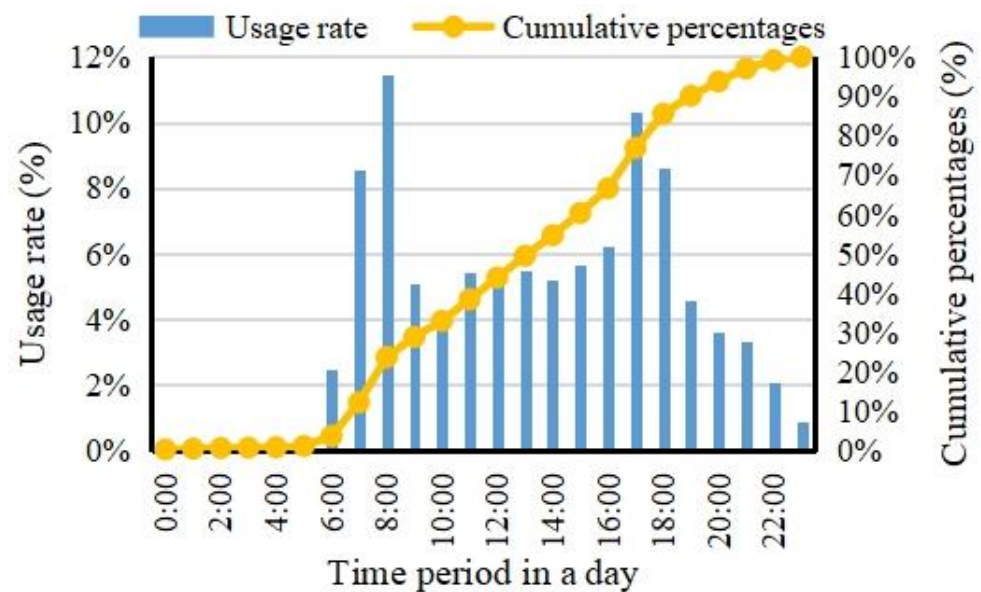


Figure 6. Temporal distributions of bicycle trips using trip start time.

Moreover, between 09:00 and 17:00, shared-bicycle usage remains relatively stable, with only minor fluctuations around lunch (11:00–13:00). After 23:00, usage declines toward its minimum and gradually rebounds after 06:00 the next day. The overall daily pattern thus reflects the varying demand for shared bicycles across time, further confirming their role as a flexible mode of short-distance transportation.

3.1.3. Spatial Distribution of Bicycle Trips

To investigate the spatial distribution characteristics of shared-bicycle trips, this study adopts a kernel density estimation (KDE) approach to analyze the spatial distribution pattern by examining the density of trip origins and destinations. The results shown in Figure 7 indicate that shared-bicycle trips are mainly concentrated in the central and western parts of Nanjing's core urban area, while the distribution in the northeast is relatively sparse.

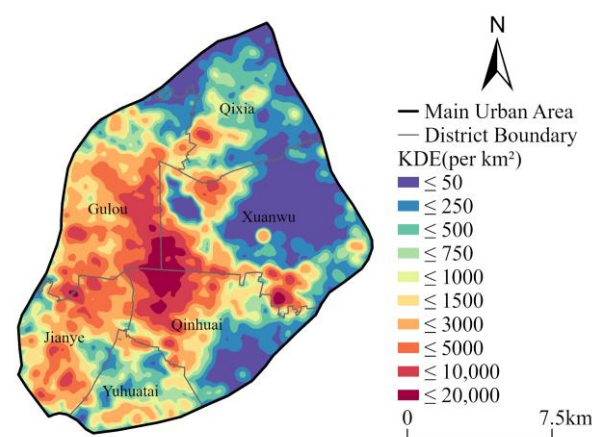


Figure 7. Distribution density of bicycle trips.

The central part of Nanjing's core urban area serves as the city's commercial hub, where numerous large-scale commercial complexes cluster and attract substantial foot traffic, thereby significantly boosting the usage of shared bicycles. The western and central-northern parts of the core area are predominantly residential, consisting of dense population clusters, which leads to higher demand for shared-bicycle services. Additionally, several major scenic spots within the core area, such as Xuanwu Lake, Zhongshan, and Mubufeng Mountain, are mainly distributed to the eastern and northern parts; the relatively low deployment demand for shared bicycles around these scenic areas results in a "vacuous" region for bicycle usage.

Overall, the spatial distribution of shared-bicycle trips in Nanjing's core urban area exhibits a pattern of "central dominance with multi-point diffusion", closely aligning with the population distribution within the core city. This characteristic reflects the higher utility of shared bicycles as a mode of short-distance transportation in densely populated and highly commercially active zones.

3.2. *Spatial and Temporal Distribution of Carbon Reductions from Shared Bicycles*

3.2.1. Results of Carbon Reduction Estimation for Shared Bicycles

This study uses the modal shares from the 2018–2019 Nanjing Urban Transport Development Annual Report [37,38]. Private car travel accounts for 36%; metro accounts for 27%; bus accounts for 22%; taxi accounts for 11%; other accounts for 4%. According to related statistics, private cars in 2018 in Nanjing were still predominantly internal-combustion-engine vehicles, with a small share of electric vehicles (about 1%) [39]. We set the shares of ICE vehicles and EVs at 99% and 1%, respectively, and assigned carbon-emission factors of 220 g/km for ICE, and 143 g/km for EV (where g/km represents grams of CO₂ emitted per kilometer traveled), with a distance-weighting factor of 1.5 per trip. This yields a private-car carbon-emission factor of 146.15 g/pkm (where g/pkm represents grams of CO₂ emitted per person per kilometer traveled). Given potential differences in data sources, calculation methodologies, and underlying assumptions, the emission factors inherently carry a degree of uncertainty. This uncertainty may influence the absolute magnitude of the estimated carbon reductions attributable to shared bicycles, yet it is unlikely to alter the overall trajectory of transportation-related carbon reductions associated with shared bicycles.

Additionally, in 2018, the total number of taxis in Nanjing was 13,354, with an annual passenger volume of 122.55 million person trips [39]. The daily average running distance per taxi is about 363.45 km, and the average trip distance per passenger is about 8 km. Consequently, the taxi carbon-emission factor is 396.13 g/pkm.

From these inputs, the final estimated carbon reduction factor for shared bicycles in the core urban area of Nanjing is 96.19 g/pkm, meaning that each kilometer rode by a user on a shared bicycle reduces carbon emissions by 96.19 g. The study estimates that the core urban area's daily total bicycle distance is 444,070.84 km, corresponding to a daily carbon reduction of about 42.72 t. Extrapolating under favorable climatic conditions, and neglecting the suppressive effects of extreme summer heat, winter cold, and precipitation (rain or snow) on cycling demand, the ideal annual carbon reduction by shared bicycles in the core urban area of Nanjing is about 15,591.04 t, which is roughly equivalent to the annual emissions of 4715 conventional fuel-powered cars. This result highlights the significant role of shared bicycles in reducing urban transportation carbon emissions.

Figure 8 presents the temporal distribution of carbon reductions from shared bicycles. From a temporal perspective, the reductions exhibit two pronounced peaks corresponding to the morning (07:00–09:00) and evening (17:00–19:00) commuting rush hours. Specifically, the morning peak accounts for 9.01 t and 21.14% of the daily total carbon reductions, while

the evening peak accounts for 8.91 t and 20.90%. Overall, reductions during the two peak periods constitute 42.04% of the daily total, underscoring the important role of shared bicycles in urban commuting. This time distribution aligns with the temporal pattern of bicycle trip distributions and further validates the commuting nature of shared bicycles.

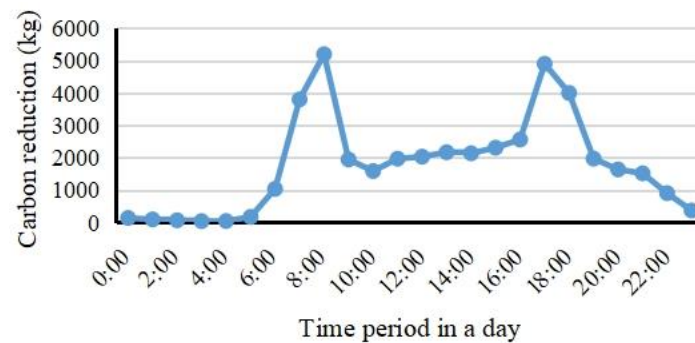


Figure 8. Temporal distribution of carbon emissions reduction.

Figure 9 shows the spatial distribution of carbon reductions from shared bicycles. The spatial pattern of carbon reductions is closely related to the spatial distribution of bicycle trips: the reductions are concentrated in population-dense areas and central zones with high commercial activity, while the reductions are comparatively lower around scenic spots and peripheral areas. This distribution effectively reflects the notable role of shared bicycles in optimizing short-distance urban travel, alleviating traffic congestion, and reducing carbon emissions.

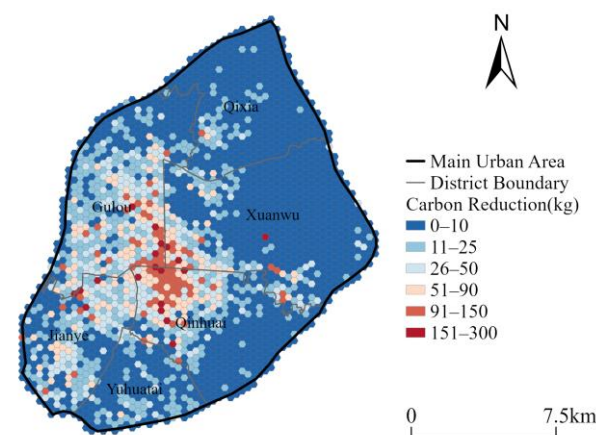


Figure 9. Spatial distribution of carbon emissions reduction.

3.2.2. Carbon Reduction Benefits of Bicycle–Metro Integration

To assess the carbon reduction benefits of coordinated travel between shared bicycles and the metro more deeply, this study centers on the metro stations in Nanjing's core urban area and establishes three buffers with radii of 50 m, 100 m, and 200 m. These buffers are treated as the spatial ranges within which shared bicycles can effectively connect with the metro (Figure 10). Within these delineated areas, bicycle trip data are extracted and carbon reduction estimates are computed, with the aim of quantifying the contribution of the feeder trips to the overall carbon reduction benefits.



Figure 10. Distribution of buffer zones around metro stations.

With a buffer radius of 50 m (Table 2), the area accounts for only 0.92% of the core urban area; yet it contributes 1.92 t of carbon reductions, representing 4.51% of the city's total shared-bicycle carbon reductions. Expanding the buffer radius to 100 m increases the area to 2.84%, and the corresponding carbon reductions rise to 3.89 t, rising to 9.13% of the total. When the radius is further expanded to 200 m, the area share becomes 8.94%, and carbon reductions markedly increase to 7.92 t, amounting to 18.58% of the total. Thus, although the spatial coverage of the buffers is small, their carbon reduction contributions are substantially higher than those of ordinary regions, indicating that shared bicycles serving as feeder modes to the metro exhibit higher carbon reduction efficiency per unit area, and highlighting the environmental benefits of coordinated travel between shared bicycles and rail transit.

Table 2. Carbon reductions from shared bicycles within buffer zones.

Distance (m)	Area Percentage (%)	Carbon Reduction (t)	Carbon Reduction Percentage (%)
50	0.92	1.92	4.51
100	2.84	3.89	9.13
200	8.94	7.92	18.58

Furthermore, this study analyzes the carbon reduction performance of feeder-bicycle usage to the metro during the morning and evening peak periods. The results are presented in Table 3: the share of carbon reductions from shared bicycles that serve as feeders to the metro during peak hours approaches 45%, with the evening peak being slightly higher than the morning peak. This temporal pattern indicates that citizens are more inclined to adopt the “shared bicycle + metro” combination during commuting peaks to improve travel efficiency and reduce carbon emissions, underscoring the critical role of coordinated travel in alleviating traffic congestion and advancing low-carbon transformation.

Table 3. Carbon reductions from shared bicycles within buffer zones at the AM/EM peak.

Distance (m)	Carbon Reduction (t)		Carbon Reduction Percentage (%)	
	AM Peak	EM Peak	AM Peak	EM Peak
50	0.45	0.45	23.51	23.53
100	0.86	0.91	22.00	23.38
200	1.59	1.74	20.08	21.96

Overall, whether judged by spatial efficiency or temporal characteristics, the carbon reduction advantages of shared bicycles used as feeders to the metro are evident.

This not only confirms their value as a key component of a green urban mobility system but also provides empirical support for future optimization of the integration between shared bicycles and rail transit to enhance the carbon reduction capability of the overall transportation system.

4. Discussion

4.1. Sensitivity Analysis of Carbon Reduction Benefits

Against the backdrop of the “dual carbon” goals, shared bicycles, as a low-carbon travel option, have drawn wide attention for their carbon reduction benefits. However, the carbon reduction impact of shared bicycles is not static; it is jointly influenced by multiple factors. To deepen understanding of the underlying mechanisms, this section discusses three aspects—changes in travel patterns, metro station layouts, and electric vehicle (EV) development—to explore the carbon reduction mechanism and development potential of shared bicycles.

(1) Impact of changes in travel patterns on carbon reduction benefits

The structure of travel demand is one of the core determinants of the carbon reduction benefits of shared bicycles. In the carbon reduction estimation in this study, the baseline scenario uses the city-wide average travel structure, but in reality, regional transportation mode choices vary significantly. For example, the central urban area has well-developed public transportation, leading residents to favor metro and walking, whereas the outskirts have lower public transport coverage, with a higher share of private-car trips. Therefore, in suburban areas with higher private-car shares, increasing the adoption of shared bicycles by residents would yield relatively more pronounced carbon reductions; in the urban core where public transport dominates, even though bicycle usage may be higher, it may substitute walking or bus travel—low-carbon alternatives—thereby yielding limited overall carbon savings. This conclusion is further corroborated by Li et al. [20]. Moreover, as the government actively guides residents to reduce private-car dependence, the share of private cars declines and the carbon reduction potential of shared bicycles within the overall travel structure rises, especially in suburban and peri-urban areas. This view is consistent with Zhang et al. [23]. These insights suggest that future urban transport planning could further compress high-carbon travel modes through policy incentives, thereby making shared bicycles’ carbon reduction contributions more pronounced.

(2) Impact of metro station layout on carbon reduction benefits

The feeder role of shared bicycles for metro transit has become an important modality in urban commuting. Many commuters adopt the “bicycle-metro-bicycle” multi-modal travel pattern to improve efficiency. Some studies indicate that a 10% increase in shared-bicycle trips is associated with a 2.3% increase in daily metro ridership [40,41]. However, metro coverage density and service levels vary across regions, directly affecting the spatial extent of shared-bicycle use and its carbon reduction effects. When metro stations are dense with broad coverage, more residents use shared bicycles as feeder tools, forming a high-frequency, short-distance, green travel structure and boosting overall carbon reductions. Conversely, in areas with limited metro coverage or small service radii, shared bicycle usage is lower and carbon reductions are more modest. Similarly, Fan et al. found that increasing shared-bicycle supply around metro stations helps alleviate peak-hour road congestion [42]. Therefore, the spatial layout of shared bicycles should be coordinated with public transit systems like the metro, especially during new metro-line planning and station siting, where consideration of feeder demand can amplify the synergistic carbon reduction effects.

(3) Impact of electric-vehicle development on carbon reduction benefits

In recent years, EVs have rapidly advanced and become a crucial force in achieving carbon neutrality in the transport sector. EV ownership for private cars continues to rise, and public transit electrification is largely complete. This trend generally lowers the carbon intensity of the transport sector, but it also poses new challenges for the carbon reduction benefits of shared bicycles. As Littlejohn notes, EVs are playing an increasingly important role in Europe's transport transition [43]. Compared with internal-combustion-engine vehicles, EVs have substantially lower per-kilometer carbon emissions; thus, when a mode replaced by shared bicycles shifts from petrol cars to EVs, the corresponding per-trip carbon reduction by shared bicycles would diminish. This effect is more pronounced in highly electrified urban areas. For example, a study in Shanghai shows that EV adoption is profoundly shaping the direction of urban sustainable transportation development [44–46]. This suggests that, in the face of ongoing carbon-neutralization targets, shared bicycles should focus more on integrated travel modes such as “shared-bicycle + metro” rather than relying solely on their own carbon reduction amounts to maintain a central position in the green mobility system.

Overall, although shared bicycles do possess certain carbon reduction capabilities, their role within the city's overall transportation system should be viewed as “coordinated optimization” rather than a primary substitution. Compared with high-capacity public transit like metro systems, the annual carbon reduction by shared bicycles is relatively modest. Shared bicycles should play a larger role in microcirculation, feeder services, and complementarity. Therefore, future pathways toward transportation carbon neutrality should strengthen integration among shared bicycles, the metro, buses, and other transport modes, promoting a modal shift and achieving a low-carbon and efficient evolution of the overall transportation system while improving travel efficiency.

4.2. Planning Policy Recommendation

Based on the above research, this paper argues that the carbon reduction potential of shared bicycles relies on integrated governance and cross-modal coordination, not on expanding a single instrument alone. A comprehensive policy mix should steer high-carbon travel toward low-carbon alternatives. Differentiated parking management and signalized pricing in urban areas can gradually raise private-car costs, increasing the attractiveness of shared bicycles, walking, and the metro. Policies must align with carbon reduction targets and social equity, avoiding burdens on low-income groups or residents on the outskirts. A tiered and affordable incentive-and-restriction framework should mobilize both firms and individuals toward low-carbon travel changes. As the costs of private cars rise, travel-structure optimization should be guided by congestion charges, carbon taxes, and favorable policies for new-energy vehicles, creating market-driven substitution effects. Incorporating a low-carbon travel points system into daily transport benefits can promote the synergistic use of shared bicycles, the metro, and walking, forming a reinforcing “green travel community.” An annual, transparent evaluation mechanism should monitor travel structure changes, carbon intensity, and incentive coverage to enable timely policy adjustments.

Coordination between metro systems and bicycles should prioritize spatial layout optimization and user experience. In areas surrounding metro stations, improved shared-bicycle parking and pickup/drop-off facilities enhance accessibility of station entrances and exits, and integrate feeder roads, dedicated cycling lanes, and safe crossing facilities to enable seamless cycling–metro transfers. The information layer of coordination is equally critical; establish a cross-operator data-sharing and navigation platform to provide real-time parking data, cross-modal routing, and closed-loop fault reporting, increasing cross-modal travel usability and expanding bicycle coverage and efficiency. Deployment and capacity

planning should be demand-driven, using mid- to long-term plans informed by week-day/weekend flows and hotspot distributions in campuses and commercial districts [47–49]. Dynamic scheduling in high-potential areas can yield greater carbon reduction benefits.

Establishing a dynamic scheduling and governance mechanism for shared bicycles is essential for sustained impact. Develop a platform with situation-awareness and decision-support that integrates geospatial big data, weather, and event information from campuses and commercial areas to identify in-demand hotspots in real time and predict supply gaps for rapid response. Regionally flexible scheduling should define deployment caps and recovery routes in hotspots like rail hubs, campuses, and commercial districts to prevent waste and over-deployment, while balancing operational efficiency and safety. Strengthen vehicle maintenance, ensure data transparency and privacy protections, and implement a governance framework that combines incentives and sanctions to maintain service quality and public trust. Future efforts should promote data integration across bicycle scheduling and public transit, taxis, and ride-hailing to form a multi-modal solution that enhances decarbonization and resilience. Strict data-use boundaries, access controls, and audit mechanisms are necessary to mitigate privacy risks and data misuse [41,50]. Phased pilots, cost–benefit evaluations, and public engagement can help reduce governance costs and social friction.

Overall, shared bicycles have notable decarbonization potential, but their role should be understood as part of a coordinated optimization rather than as a primary substitute. Compared with high-capacity transit such as metro systems, the annual emissions reductions attributable to shared bicycles are relatively modest. The pathway to carbon neutrality should emphasize micro-circulation, feeder functions, and complementary roles for shared bicycles, with deeper integration into the metro, buses, and other modes to improve system-wide decarbonization and operational efficiency. With careful attention to equity, data governance, and public participation, shared bicycles can be more effectively integrated into the city’s broader green transition [28].

4.3. Study Limitations and Future Work

Although this study provides a systematic, multidimensional assessment of the carbon reduction benefits of shared bicycles, several limitations remain that should be addressed in future research. First, some data used in this study, such as travel-mode sharing and the penetration of electric vehicles, are estimated or suboptimal, lacking sustained, real-time time-series support. This limitation may affect the stability and reproducibility of the findings. Future work could integrate citywide travel surveys, connected vehicle (V2X) platform data, and mobile-origin travel records to build and maintain dynamic datasets, thereby improving model accuracy and sensitivity to spatio-temporal variation. Second, the carbon-emission factors used are based on national statistical indicators and do not fully account for differences in energy consumption, operating intensity, and contextual conditions across transportation modes in practice. Subsequent research should incorporate life cycle assessment and context-specific emission factors, explicitly considering regional differences and varying operating regimes to develop a more comparable and transferable framework for carbon-emission assessment. Moreover, a key limitation concerns the ride-trace data for bike-sharing in Nanjing, which are only available for the year 2018. This data restriction may limit the ability to capture recent changes in routing patterns, mode availability, and network conditions that could influence cycling distances and demand in subsequent years. In addition, while the study’s focus on central urban areas of Nanjing provides a degree of representativeness, it is not universally applicable to all cities; regional heterogeneity could affect external validity. Subsequent work should expand to multi-city and multi-sample-type comparisons to test generalizability and adaptability, and explore

how regional characteristics modulate carbon reduction effects [51]. Finally, it is advisable to incorporate uncertainty analysis and sensitivity analysis at the methodological level, and to conduct robustness checks on key parameters to strengthen the credibility of the findings and policy recommendations.

5. Conclusions

This study develops a carbon reduction accounting model for shared bicycles and conducts an empirical analysis using Nanjing as a case study. It examines the spatio-temporal distribution of carbon reduction benefits under different scenarios and assesses the carbon reduction impact of shared bicycles when serving as feeder modes to the metro. The main conclusions are as follows: First, in Nanjing, shared bicycles predominantly support short trips, with the average trip distance and duration in the central urban area being around 1287.21 m and 8.70 min, respectively. Second, temporally, bicycle usage exhibits a pronounced bi-modal distribution, with peak demand during the morning and evening rush hours reflecting a clear diurnal cycle. Third, spatially, bicycle trips display a central concentration with multi-point diffusion, showing higher usage in densely populated and commercial districts. Fourth, using 1 km of shared bicycle travel in the central urban area reduces carbon emissions by about 96.19 g, with daily reductions of around 42.72 t and annual reductions of about 15,591.04 t. Fifth, in terms of mitigation benefits, shared bicycles that serve as feeders to the metro yield the largest reductions: up to 7.92 t, accounting for 18.58% of total reductions. During the morning and evening peaks, the share of metro-feeder bicycle emissions reductions approaches 45.00%, indicating stronger environmental value for integrated bicycle–metro travel than for conventional shared bicycles. Sixth, as public awareness of low-carbon travel increases, shifts in travel modes, metro station layouts, and the adoption of electric vehicles continue to influence the carbon reduction outcomes of shared bicycles.

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