Deciphering the Scaling Laws and Spatial Structure in Urban Micro-mobility: Empirical Evidence from Bike-Sharing in Shanghai

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Abstract
Micro-mobility, including bicycles and other low-speed vehicles, significantly enhances urban mobility and provides a sustainable alternative to traditional transport modes. Despite extensive research on the universal laws in urban mobility and its impacts on urban growth, the empirical distribution and allometric scaling phenomenon of micro-mobility like bike-sharing remain poorly understood. This study delves into the scaling laws and spatial dynamics specific to micro-mobility using bike-sharing data from Shanghai. The number of cycling visitation to any location in the city is inversely related to the square of the cycling distance multiplied by the frequency. This scaling relationship is controlled by a parameter that describes the attractiveness of different locations in the city for cycling. It is noteworthy that the size distribution of the spatial clusters, as determined by spatial clustering analysis of the attractiveness, conforms to Ziff's law. This implies that the spatial structure underlying the cycling is a highly ordered, hierarchical system, which coincides with the central place theory. This study provides a framework that can effectively predict the distribution of micro-mobility within a city, which can help to understand and utilize the dynamics of complex urban systems in order to promote more sustainable urban mobility solutions.

Keywords: Micro-mobility; bike visitation; scaling laws; spatial clusters; Zipf's law

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Introduction

The burgeoning field of micro-mobility has emerged as a critical component in addressing the complexities of urban transportation and sustainability (Reck et al., 2022, Abduljabbar et al., 2021, Madapur et al., 2020). As cities grapple with escalating traffic congestion and environmental concerns, micro-mobility offers an innovative solution by promoting bicycles and other lightweight, low-speed vehicles as viable alternatives to traditional motorized transport (Abduljabbar et al., 2021, Steinacker et al., 2022, Diao et al., 2021). This shift not only promises to enhance urban mobility but also aligns with broader sustainability goals by reducing carbon emissions and improving public health (Diao et al., 2021, Zhang and Mi, 2018, Abduljabbar et al., 2021). During the outbreak of the COVID-19 pandemic at the end of 2019, bike-sharing systems were responsible for more than half of urban transportation during the lockdown period (Zhu et al., 2022, Shaer et al., 2021, Hu et al., 2021, Teixeira and Lopes, 2020).

Extensive research on urban mobility has explored the scaling laws that describe how the empirical distributions of urban mobility change with various factors (Dong et al., 2022, Schlapfer et al., 2021, Song et al., 2010, Yan et al., 2013, Wang et al., 2014). For instance, it has been shown that the taxis visitation in various locations in city follows a power-law distribution (Zheng and Zhou, 2017). Studies have found that this power-law distribution is influenced by factors such as travel distance (Schlapfer et al., 2021, Zheng and Zhou, 2017, Wang et al., 2023). Similarly, research into how population density and urban form affect mobility patterns reveals that larger cities exhibit non-linear increases in travel times and transportation costs due to congestion (Louf and Barthelemy, 2014). These studies highlight the complex interdependencies between urban growth, mobility, and infrastructure. However, most existing research has focused predominantly on conventional modes of transportation, such as cars and public transit, with less attention given to micro-mobility programme like bike-sharing. Although micro-mobility offers potential sustainability benefits by reducing reliance on motorized transport, its dynamics within the urban systems remain underexplored. Furthermore, studies have investigated the relationship between the built environment and cycling activities, emphasizing how urban design factors influences cycling frequency and distance (Cervero and Duncan, 2003, Moudon et al., 2005, Cervero et al., 2009, Buehler and Dill, 2015, Xu et al., 2019). Despite the contribution of these studies, they tend to remain descriptive and static, failing to fully take into account the underlying phenomenon of allometric scaling in urban mobility (Alessandretti et al., 2020, Batty, 2013, Bettencourt, 2013). This gap highlights the need for more dynamic studies that can better explain the allometric scaling phenomenon of micro-mobility systems and their impact on urban dynamics.

This study seeks to address the gaps in understanding the specific scaling laws and spatial dynamics of urban micro-mobility, using extensive bike-sharing data from Shanghai. By analyzing cycling trajectories and usage patterns, this study confirms that cycling visitations are strongly influenced by cycling distance and frequency, exhibiting a power-law distribution, which is modulated by a parameter reflecting the attractiveness of various city locations for cycling. Notably, the size distribution of these attractiveness clusters, as determined by spatial clustering analysis, adheres to Zipf's law. This finding suggests that the spatial structure of cycling mobility in the city is highly ordered and hierarchical, aligning well with central place theory. The results underscore the importance of integrating these insights into urban planning and transportation strategies, emphasizing how micro-mobility can play a pivotal role in shaping sustainable urban growth. Ultimately, this paper advances the discourse on the universal laws of micro-mobility and contributes a novel framework for enhancing urban planning through the lens of bike-sharing data.

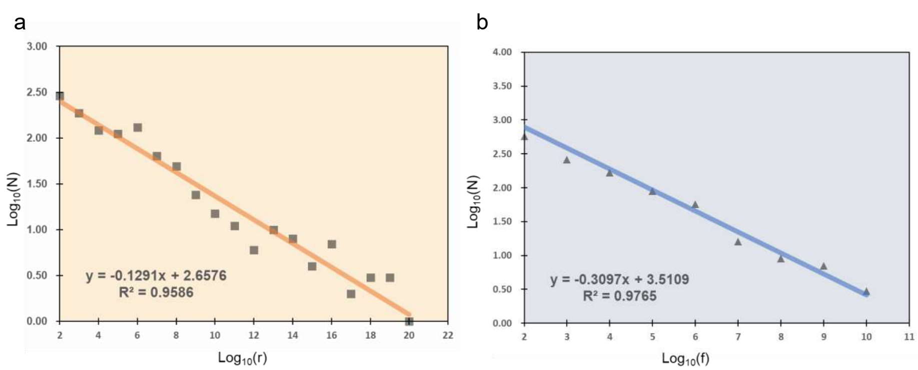
Results

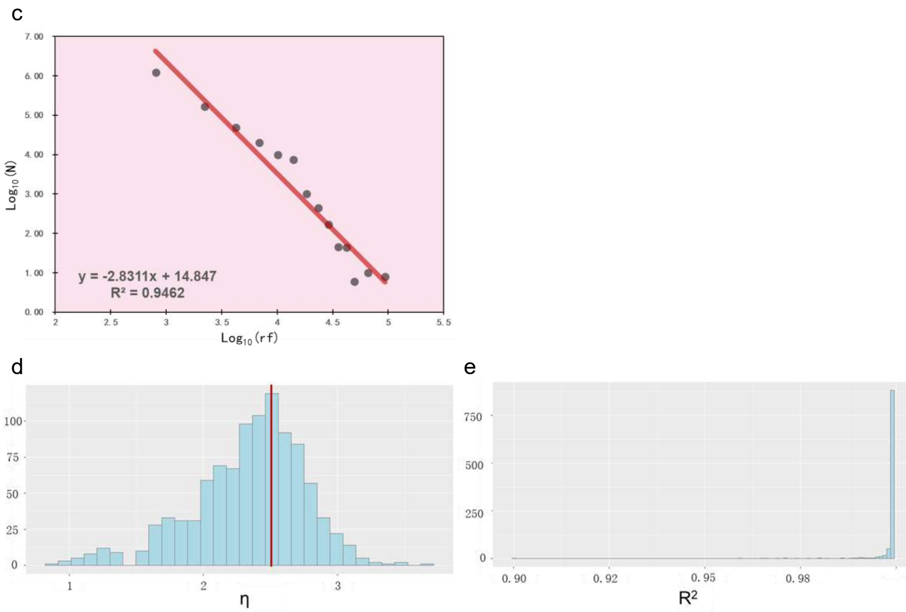
The scaling laws of Micro-mobility in Shanghai

We fitted the relationship between the number of bike visitations and the travel distance or the frequency of cyclists visiting the same location by bike in a week separately (Fig. 1a, 1b), revealing that the number of visitations N decreased proportionally with the increasing travel distance r when only considering distance. When considering the travel frequency f over a continuous week, N also decreased proportionally with increasing f for each cyclist. Similarly, when treating distance r and frequency f as a combined variable rf, the relationship between rf and N followed a power-law distribution with a fixed exponent between 2.4-2.8 (Fig. 1c, 1d). This implies that the number of bike visitations to any location in the city depends solely on the travel distance and frequency. Therefore, the relationship between the bike visitations to any location i in the city and the distance-frequency can be described as a power function (Equation 1).

$$N_i = \frac{\mu_i}{(rf)^{-\eta}} \qquad (1)$$

Since the power-law exponent η is a fixed value, the constant term μ_i determines the magnitude of bike trip attractivity at any location in the city, which can be considered as the " attractiveness" for micro-mobility. We conducted power-law fits for the top 30 grid cells with the highest bike trip attractiveness in Shanghai, and found that the power-law relationship was significant with a fitting R^2 of around 0.99 (Fig. 1e). Moreover, this scaling law of bike was not influenced by the specific spatial position of the analyzed unit, indicating its universality (Fig. 1f).

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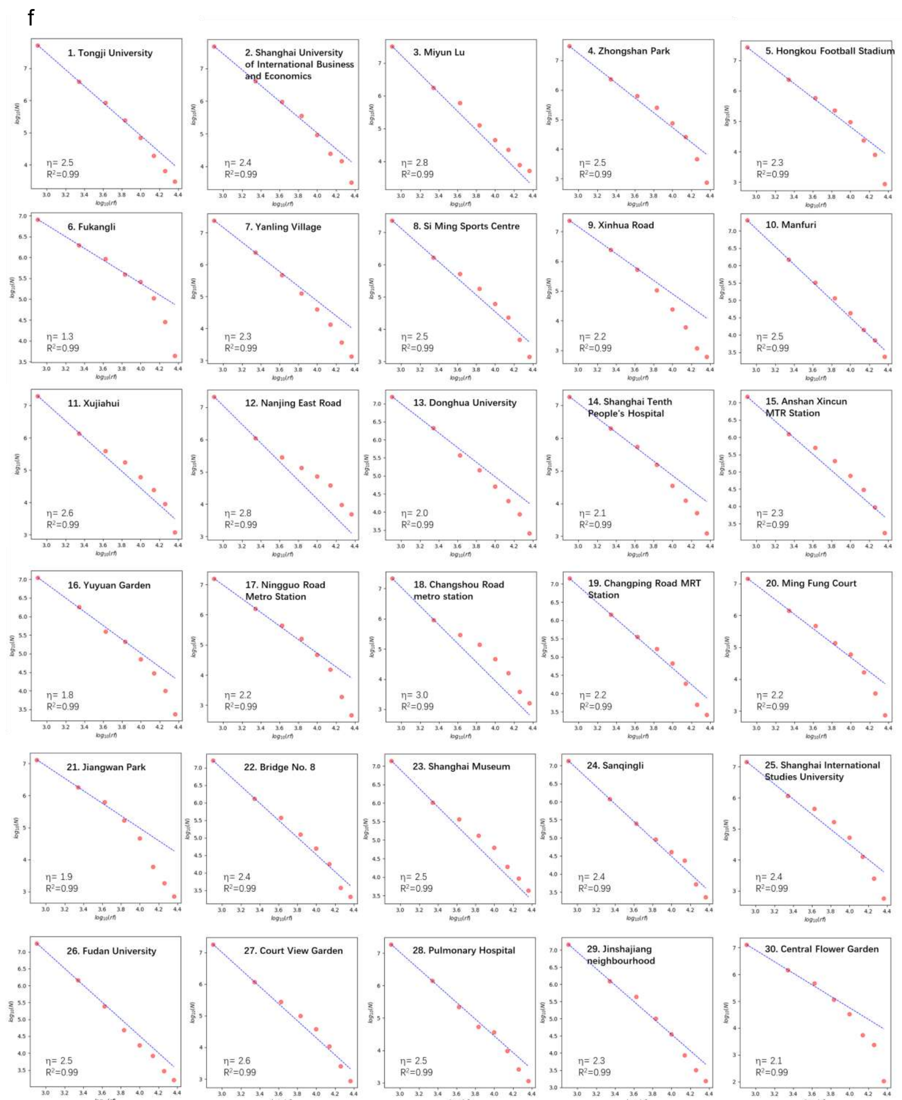

Fig.1| The scaling laws of bike-sharing visitations. a, The power-law distribution between travel distance r and bike visitations. **b**, The power-law distribution between frequency f and bike visitations. **c**, For a fixed f, the bike visitations $N_i\,(r, f)$, decreases with increasing r with a fixed exponent. **d**, The empirical distribution of power-law exponents η. **e**, The fitting R^2 of the distance–frequency distribution. **f**, The Distance-frequency laws of top 30 grids in Shanghai.

Attractiveness of Micro-mobility visitations and its spatial structure

As previously described, this study has derived a power-law function that indicates the bike visitation of any location in the city only depends on the constant term μ_i when the product of travel distance and frequency is constant. Therefore, the constant term μ_i in the power-law function can be considered as the attractiveness of a location for bike visitations, which characterizes the spatial interaction of urban internal space based on bike-sharing flows (Fig. 2a).

By observing the spatial distribution characteristics of μ_i, a significant phenomenon can be observed, that is, grids with higher attractiveness tend to exhibit an agglomeration distribution, forming some larger central clusters, such as Jing'an Temple and People's Square, Shanghai. Grids with lower attractiveness tend to be clustered around these central clusters. Meanwhile, outside a certain spatial range, some smaller sub-central clusters with a larger number of grid units can be found. This spatial structure shows a strong correspondence with the central hierarchy structure in the central place theory. According to previous research on the spectrum of human flow based on mobile phone signaling data, this center-like distribution system, which is similar to a hierarchical scale, originates from the agglomeration effect of commercial and public service facilities in the city (Schlapfer et al., 2021).

To further verify the hierarchical nature of the spatial distribution of bike attractiveness, the City Clustering Algorithm (CCA) was employed to identify spatial clusters with different levels of attractiveness (Fig. 2b). The CCA involves setting a threshold for the attractiveness parameter μ and setting all values below the threshold to zero. Then, contiguous spatial locations with non-zero values are recursively merged into spatial clusters until all non-zero grid cells have been merged. Through the CCA, spatial clusters with significant differences in attractiveness can be effectively identified.

Subsequently, the size of each spatial cluster was fitted to a power-law relationship, known as Zipf's law, which is commonly used to describe the basic principle of urban size growth (Fig. 2c). The fitted results showed that the size distribution of the spatial clusters emerging from the bike flow conformed to Zipf's law, and the size-rank relationship was approximated by a power-law relationship with an exponent of 1.08. This indicates that there is a highly ordered hierarchical structure in the spatial locations towards which the bike flow is directed.

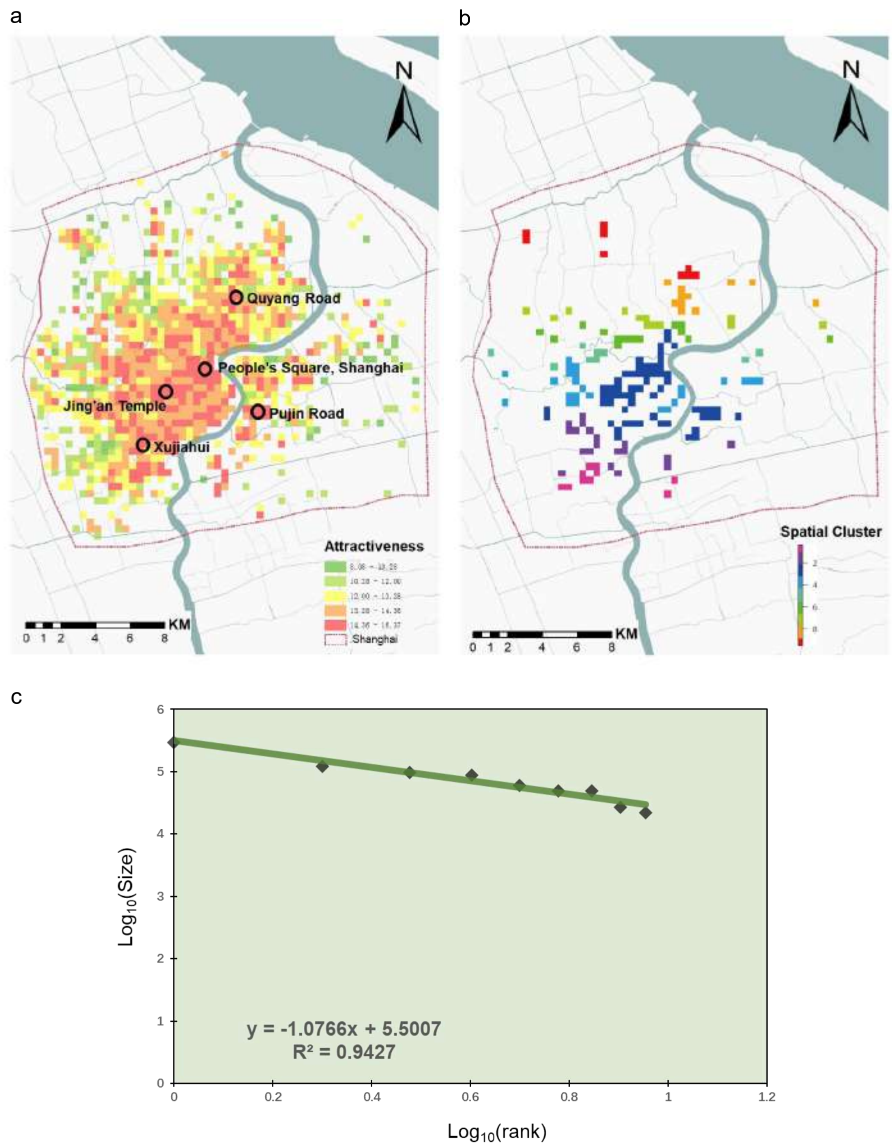

Fig.2| Spatial structure of micro-mobility attractiveness. a, Spatial distribution of the attractiveness μ_i. **b**, Spatial clusters based on City Clustering Algorithm. **c**, Rank–size distribution of the attractiveness of spatial clusters.

Discussion

The results reveal a empirical power-law distribution in the relationship between bike visitations and travel distance and frequency across varying locations in Shanghai. This finding corroborates the existence of scaling laws in urban micro-mobility, which have been observed in other modes of transport across different urban settings (Bettencourt, 2013, Schläpfer et al., 2014, Dong et al., 2022, Schlapfer et al., 2021). Our results innovatively confirm the presence of allometric scaling phenomenon within short-distance, high-frequency micro-mobility patterns. This suggests that in urban settings, cycling activities are highly concentrated, with most cycling activities occurring over shorter, more frequent trips, while longer trips are relatively rare. The cycling power exponent discovered in this study is greater than 2, higher than the exponents for car travel found in existing studies, aligning with our understanding that micro-mobility is more sensitive to distance and frequency (Schlapfer et al., 2021). Moreover, this finding provides deep insights into the growth mechanisms of cycling networks. The presence of a power-law distribution suggests that preferential attachment and rich-get-richer effects exist within the cycling network (Fabiano L. Ribeiro, 2021). New or casual cyclists are more likely to choose cycling locations that are frequently visited, leading to disproportionate growth in activity at certain locations due to their accessible location, well-maintained facilities, or good connectivity. Over time, these areas will further consolidate their status as major cycling hubs, attracting even more cyclists. Urban planners need to consider existing cycling patterns and network effects when designing cycling infrastructure, by planning multiple attractive nodes or enhancing the interconnectivity of the entire network. Urban transport networks are dynamically evolving and require continuous monitoring and adjustment. Understanding and applying the principles of preferential attachment and rich-get-richer can assist urban planners in timely strategy adjustments to meet the changing needs of urban development and resident behavior patterns.

Furthermore, our findings indicate that the scaling phenomenon in micro-mobility is controlled by a parameter that describes the attractiveness of different locations in the city for cycling. It is noteworthy that the size distribution of the attractiveness clusters conforms to Zipf's law. This implies that the spatial structure underlying cycling mobility is a highly ordered, hierarchical system, which coincides with the central place theory. This orderliness likely stems from the varying influence of urban services and facilities provided at different sites (Schlapfer et al., 2021). At the micro-scale, typically where micro-mobility occurs, there are still multiple attractive nodes within the city that play central roles in driving mobility. These nodes may correspond to cultural facilities, commercial areas, parks, and other public spaces (M Batty, 1989, Tian et al., 2015). This pattern indicates that even at micro scales, the city structure exhibits fractal characteristics; that is, every part of the city, regardless of size, may reflect the structural features of the entire city. Such ordered spatial distribution suggests that the form and function of the city maintain consistency and continuity across different scales, with each community or neighborhood acting as a microcosm of the city structure. These findings not only enrich our understanding of the spatial structure at the micro-scale within cities but also provide valuable theoretical and empirical support for urban planning and sustainable transportation development. This insight emphasizes that even at the local scale, the design and planning of urban spaces must consider their complexity and inherent orderliness.

In conclusion, this study presents novel evidence regarding the empirical distribution and allometric growth of intra-urban micro-mobility. It is demonstrated that this short-distance, low-speed sustainable mode of transportation is subject to scaling laws, in a manner analogous to other forms of mobility. Furthermore, the study reveals the underlying spatial structure that governs the scaling law of micro-mobility. This structure is characterized by a highly ordered and hierarchical spatial configuration, influenced by factors such as "preferential attachment" and the "rich get richer" effect. This study provides urban planners and policy makers with a robust analytical framework that can effectively predict the distribution of micro-mobility within a city. This framework can be used to understand and utilize the dynamics of complex urban systems in order to promote more sustainable, efficient, and convenient urban mobility solutions. For future research, it is essential to conduct longitudinal studies to assess the temporal stability of these scaling patterns and delve into the causative mechanisms behind the observed power-law distributions and spatial clustering. Such studies will enrich our understanding of how urban micro-mobility systems evolve over time, offering insights that could refine current urban planning and policy strategies.

This study acknowledges several limitations. First, the temporal scope of the bike-sharing data used is confined to a single week. This short duration may not adequately represent the distance-frequency distribution of cycling trips over a more extended period, potentially limiting the generalizability of the cycling visit patterns observed. Second, while this study introduces an attractiveness parameter, its mathematical and practical significance, along with its correlation with the characteristics of the built environment, requires further exploration to fully understand its implications. Lastly, as the analysis focuses solely on central city of Shanghai, the applicability of the findings to other urban settings, both within China and globally, may require additional validation.

Data

This study utilizes large-scale bike-sharing data to explore the universal laws of cycling visits across various districts within Shanghai. The focus is specifically on the city center, defined as the area within the Outer Ring Road. This region, spanning approximately 660 square kilometers, includes the historically established urban districts of Huangpu, Xuhui, Changning, Yangpu, Hongkou, Putuo, and Jing'an, as well as the Inner Outer Ring Road areas of the Pudong New Area (Fig. 3a). Shanghai's location at the eastern edge of the Yangtze River Delta provides relatively flat terrain and a climate favorable for cycling. As one of the pioneering cities in adopting bike-sharing systems, Shanghai boasts a fleet of over 1.3 million bicycles, facilitating frequent usage among a relatively stable user base.

The data utilized in this study is the Shanghai shared bike order dataset provided by Meituan. This dataset encompasses over 4.6 million shared bike orders from over one million anonymous users over the course of a single week (June 17th, 2019 to June 23rd, 2019). The data includes order number, user number, bike number, start time, start location latitude and longitude, end time, end location latitude and longitude, and other pertinent information.

The preprocessing of the bike-sharing dataset in this paper is comprised of three distinct steps (Fig. 3b). In the initial stage of the study, the area under investigation is divided into a regular grid comprising square cells of uniform dimensions, with a side length of 500 meters. A total of 2,551 grid cells were obtained within the central city of Shanghai. Subsequently, the bike-sharing trip data with spatial and temporal location information were intersected with the regular grid in ArcGIS, and the bike-sharing data with obvious anomalies were excluded. In the second step, the set of individuals who have accessed the cycling network in each grid cell is identified. For each grid cell, this paper calculates the weekly frequency of cycling visits to the grid cell within a consecutive week's time span. Concurrently, the distance traveled by cyclists is calculated based on the starting point of their journey. In the third step, the riding visits are obtained by calculating the riding distance and riding frequency, respectively. The initial distance for the riding distance grouping is set at 800 metres, with the riding visits within each distance group calculated sequentially with an equal distance bin of 300 metres.

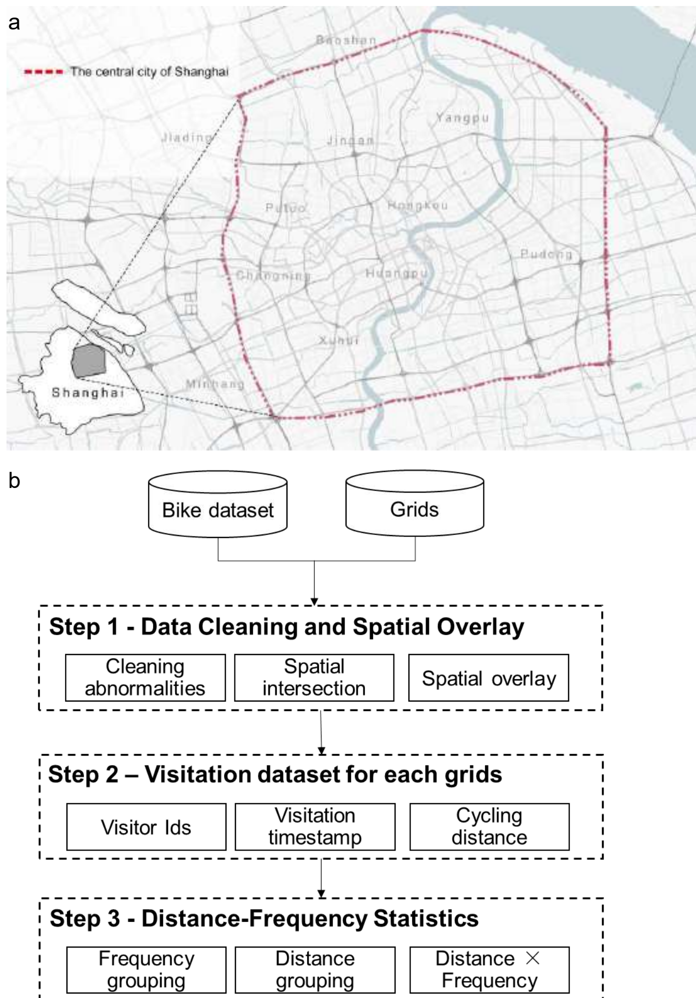

Fig.3| Data. a, Study area. **b**, Data pre-processing.

Methods

Scaling laws are known to exhibit power law distributions, which can reflect self-similar features in the process of urban scale growth or scaling of human travel behavior. This phenomenon has been observed in various studies, including those by Batty (2019), Schläpfer et al. (2021), Gong et al. (2021), Batty et al. (1989), Rybski et al. (2019), and Longley et al. (1989). In this paper, we employ the power function form of the scaling law to fit the relationship between cycling and distance and frequency. This reflects the quantitative scaling relationship between cycling visits and cycling distance and frequency. The functional form is as follows (Equation 2).

$$N = Y_0 X^{\eta} \qquad \text{(Equation 2)}$$

Where, the number of bike visitations to any location in the city, denoted by N, is a function of the travel distance, frequency, and the product of distance and frequency, which is represented by N. The parameters of the power function, denoted by Y_0 and η, influence the scaling factor, which is typically fixed (Batty, 2015, Batty et al., 2008). The coefficient, Y_0, influences the power-law relationship. The simultaneous application of logarithms to both sides of Equation 2 yield the linear functional form (Equation 3).

$$LogN = \eta LogX + logY_0 \qquad \text{(Equation 3)}$$

Where, the slope of the fitted straight line for a linear function represents the power exponent of the power function, denoted by η. Consequently, the logarithmic approach to fitting was employed in this study (Equation 3).

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