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The impact of heterogeneous accessibility to metro stations on land use changes in a bike-sharing context

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A R T I C L E I N F O

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A B S T R A C T

The integration of urban rail transit and land use has been adopted as a crucial approach to fostering compact development in cities. Proximity to rail transit stations can increase the probability of land use changes, while few studies have analyzed the spatial heterogeneity of the impact of rail transit on land use changes. This study proposes a distance-decay function to delineate the spatial heterogeneity of metro station accessibility using bike-sharing data and examines the impact of metro stations accessibility on land use changes. Jiading New Town in Shanghai, China, is selected as our study case. By utilizing a non-linear distance-decay function to delineate metro station accessibility as a driving factor for training neural networks in a vector-based cellular automata model, an improvement in simulation accuracy is achieved compared to the model using a linear distance-decay function. This study could help establish more efficient strategies for promoting integrated development of rail transit and land use. The significance of this study lies in the generality of the optimized land use vector-based cellular automata model considering the spatial heterogeneity of metro station accessibility, which could also be applied to other situations, such as considering the accessibility to bus stops and road networks.

1. Introduction

Transit-oriented development (TOD) is an effective strategy for promoting sustainable development in cities by strengthening the connection between land use and transportation (Gao et al., 2023; Loo et al., 2010). TOD densifies the catchment areas of transit stations, offering a mix of residential, commercial, and office uses, and increasing accessibility to destinations, which further contributes to land use changes (Yang et al., 2021). The impact of urban rail transit on land use has been validated through many urban practices, such as Madrid (Calvo et al., 2013), Portland (Dong, 2016), and Shanghai (Du et al., 2023). Its impact on land use changes has also been frequently investigated by existing literature (Ibraeva et al., 2020; Cordera et al., 2019; Gao et al., 2023).

Proximity to urban rail transit increases the probability of land use changes (Fu et al., 2024; Hurst and West, 2014). Land use parcels are more likely to be influenced in the area closer to a rail transit station (Bhattacharjee and Goetz, 2016; Hurst and West, 2014; Pan and Zhang, 2008). However, the land use change probability is non-linearly associated with the proximity to rail transit stations (Ding et al., 2021). It is difficult to use a smooth straight line to delineate the effect of rail transit accessibility on urban development (Gao et al., 2023). Recently, more studies have applied advanced machine learning models to reveal the non-linear association between urban rail transit and land use

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(Abdollahpour et al., 2024; Peng et al., 2023a). Although existing literature has recognized the impact of rail transit on land use is spatially heterogeneous, few studies have investigated the impact's spatial heterogeneity in a non-linear form. Therefore, the first contribution of our study is to measure accessibility to rail transit stations using a non-linear distance-decay function, which can better capture the spatial heterogeneity of urban rail transit on land use changes than a linear distance-decay function.

Accessibility, as a widely discussed concept in Geography and Transport, is crucial in evaluating the relationship between urban rail transit and land use. Distance-decay accessibility has been used to investigate spatial heterogeneity of urban rail transit's impact on land use changes in various forms, such as linear (Brons et al., 2009) or log-linear (McIntosh et al., 2014). The practice of TOD usually relies on mode-based thresholds to distinguish different catchment areas, such as using a walking distance (e.g., 500 m) to determine a "primary area" as a walkable environment or using a cycling or driving distance to determine a "secondary area" accessed by bike or car (Ibraeva et al., 2020). However, when investigating the impact of urban rail transit on land use changes, most previous literature only considered the impact threshold determined by walking while cycling-based accessibility has often been ignored. Associated with various environmental and health benefits like reducing air pollution and traffic congestion and encouraging physical activities, the integration of rail transit and bike-sharing has been increasingly popular in recent decades (Aghaabbasi and Chalermpong, 2023; Chen et al., 2022b; Zhang et al., 2019b). Bike-sharing can improve the accessibility to rail transit systems by providing on-demand first/last-mile services (Peng et al., 2023a). The combined use of rail transit and bike-sharing plays a pivotal role in promoting sustainable development in cities (Sun et al., 2024). On the other hand, the estimation of the distance-decay accessibility depends on traditional travel surveys, which are often cost-expensive in the collection and could be biased in terms of the data sample. In contrast, spatial-temporal big data provide new opportunities to explore distance-decay accessibility to rail transit stations. Bike-sharing trajectory data generated from bike-metro feeder trips could help delineate the catchment area of rail transit stations (Wu et al., 2021). Therefore, our second contribution is to consider the cycling-based catchment area of urban rail transit and examine non-linear distance-decay accessibility by using dockless bike-sharing trip data.

Cellular Automata (CA) models are one of the most widely used approaches to simulate land use changes (Arsanjani et al., 2018; Penfound and Vaz, 2024; Li et al., 2022). It has also been used to simulate the land use changes surrounding rail transit stations (Fu et al., 2024). Most previous CA-related studies are raster-based, treating regular grids as basic spatial units. Recently, vector-based CA (VCA) models have gained popularity for their ability to better simulate land use changes by directly using land parcels (Yao et al., 2024; Zhuang et al., 2022). In the CA simulation, accessibility is a main factor driving land use changes. However, accessibility to various facilities (including rail transit) is often measured using Euclidean distance, which is incapable of capturing non-linear impact. Therefore, the third contribution is to incorporate non-linear distance-decay accessibility to rail transit stations as a driving factor in a VCA model to simulate land use changes.

This study aims to examine the impact of urban rail transit on land use changes, considering the spatial heterogeneity of metro station accessibility using bike-sharing trajectory data in a cycling context. The metro system, which contains a set of rail transit stations primarily run below the surface, is a popular urban rail transit mode serving a large share of the trips generated by citizens and plays a crucial role in optimizing land use and promoting urban sustainability. We take Jiading New Town in Shanghai as our case study and the bike-sharing data provided by a leading shared micro-mobility service provider (i.e., Mobike) as our main data source. The land use change process is simulated using a VCA model. Specifically, our research questions are: (1) Could the non-linear distance-decay accessibility to metro stations better capture the impact of rail transit on land use changes than the linear one? (2) How much does the accessibility to metro stations matter in land use changes? Our analysis can help urban planning authorities and transit management agencies to make reasonable management strategies and land use policies to guide metro investment and planning, and eventually lead to high-quality transit-oriented development.

The paper is organized into the following sections: Section 2 offers a literature review on the impact of rail transit on land use changes; Section 3 introduces the study site and data description; Section 4 presents the methodology; Section 5 provides the results of our data analysis and discussions; Finally, Section 6 presents our conclusions.

2. Literature review

2.1. The impact of urban rail transit on land use changes

Urban rail transit has a great impact on its surrounding land use. It attracts various facilities such as government agencies, office buildings, and cultural venues to be located nearby (Ratner and Goetz, 2013). Transit-oriented development, as a land-use and transportation planning strategy, leads to land use changes around metro stations (Ibraeva et al., 2020). Land use changes are closely intertwined with land value, which is intrinsically linked to the distance to rail transit stations (Cordera et al., 2019; He, 2020).

The impact of urban rail transit on land use has been demonstrated to be spatially heterogeneous by existing studies. Pan and Zhang (2008) found that a higher changing level of land use and land value may more frequently occur in core areas (or inner buffer zones) than in outer areas surrounding metro stations. According to the bid-rent theory, prime locations with high accessibility can attract heightened economic activity and drive dynamic competition, notably the core areas surrounding stops and stations, leading to changes in land use (Cervero and Kang, 2011). Land use changes of high rent-producing uses like residential and commercial land were higher than low rent-producing uses like industrial land use after the rail transit development in Beijing (China) (Zhao et al., 2018). Hurst and West (2014) compared the differential effects of proximity to rail transit stations on land use parcels around the stations in Minneapolis (The United States). They found that the parcels that were closer to the stations were more influenced. Bhattacharjee and Goetz (2016) investigated how different types of land use changed concerning the land's distance to the rail transit system in the Denver metro region (the United States). They concluded that land use changes were significantly more affected in the area closer to the rail transit system, especially the changes in commercial land.

While existing studies have confirmed the spatial heterogeneous impact of urban rail transit on land use changes, they failed to sufficiently investigate the non-linearity attribute of spatial heterogeneity, which means the probability of land use changes does not linearly increase as the distance to rail transit decreases. Ding et al. (2021) identified the existence of a non-linear and spatially heterogeneous relationship between land use and transportation in Nanjing, China. Their results challenged the commonly accepted assumption of linearity and spatial homogeneity. Gao et al. (2023) developed a gradient boosting decision trees model to examine the relationship between public transit accessibility and urban development taking a mountainous city (i.e., Chongqing) in China as an example, revealing a significantly non-linear influence of accessibility to metro stations on urban development. Neglecting the non-linear effect may potentially lead to false conclusions about the land use and transportation relationship. In recent years, an increasing number of studies have explored the potential of advanced machine learning models to reveal the non-linear relationship between urban rail transit and land use. However, instead of directly investigating the impact of urban rail transit on land use changes using a simulation-based method (e.g., CA), these studies are more interested in revealing the general non-linear associations between land use and urban rail transit, such as the impact of land use patterns on metro ridership (Peng et al., 2023a), mode shares of rail stations (Abdollahpour et al., 2024) or urban vibrancy in the catchment areas of metro stations (Peng et al., 2023b).

2.2. Urban rail transit station accessibility

Accessibility can be defined as the potential for how residents' activities interact with their destinations. It typically consists of the elements of land use, transportation, time, and individuals (Gao et al., 2023; Willberg et al., 2024). Accessibility is crucial in the evaluations of land-use and transportation relationships and strategies (Aljoufie, 2014; Geurs and Van Wee, 2004). It is directly related to the transportation efficiency and land use patterns (Yang et al., 2020). Besides, accessibility to rail transit is one main factor of the spatial heterogeneous impact of urban rail transit on land use (Cervero and Duncan, 2002). Based on the land-use transportation feedback cycle (Wegener and Fürst, 2004), rail transit accessibility causes spatial heterogeneity of attractiveness and results in land use changes.

Existing studies have adopted various forms of distance-decay accessibility to investigate the spatial heterogeneity of urban rail transit's impact on land use. It can be in a linear form, which assumes that as the distance to urban rail transit increases, the impact of rail transit on land use linearly decreases (Brons et al., 2009; Givoni and Rietveld, 2007). Mathematically, these relationships are commonly formulated in a linear form between rail transit and urban development (Brons et al., 2009). The distance-decay accessibility to urban rail transit has various thresholds depending on different travel modes, such as walking, cycling, and driving. The concept of TOD distinguishes the "primary area" as a walkable environment with major commercial and employment functions, while the "secondary area" refers to a broad area accessible by bike, bus, or car (Ibraeva et al., 2020). With the popularity of bike-sharing and e-hailing, the "secondary area" has become larger and more important, especially in the suburbs (Lin et al., 2019). The metro station area distinction indicates various degrees of accessibility within different zones, which are sometimes named pedestrian catchment areas (Jun et al., 2015) and bike catchment areas, respectively (Li et al., 2021; Zhao and Deng, 2013).

However, previous studies have primarily focused on the impact threshold of primary areas (or walking catchment areas). It is conventionally assumed that people's maximum tolerance of walking distance is within a range of [400 m, 800 m] to reach a metro station (Bivina et al., 2020). Additionally, cycling, including bike-sharing, has been identified as another major mode of access to metro stations (Lin et al., 2019; Guo and He, 2020). Compared to walking access, bike-metro transfer trips have often been overlooked. In recent years, transfer cycling from or to rail stations has become an important and effective way to solve the "first and last mile" problem around rail stations (Wu et al., 2021). Recent studies have shown varying perspectives on cycling distance thresholds, such as the distances of metro stations to residential land (Zhao and Li, 2017).

Conventionally, the estimation of the distance-decay accessibility heavily relies on various travel surveys. However, the survey collection is usually labor-intensive, cost-expensive, and often biased because the surveys are difficult to conduct without many investigators and are influenced by personal experiences. The choice of data greatly affects the quality of the results (Van Soest et al., 2020). Recent studies have used emerging urban big data (e.g., GPS-tracked data, and smart card data) to estimate rail transit accessibility and corresponding catchment areas (Eom et al., 2019; Zhou and Yang, 2021). For example, Lin et al. (2019) analyzed the spatial-temporal distributions of trips around rail stations using metro station-related data and GPS-tracked bike data, which provided detailed trip information. Chen et al. (2022a) used smart card data to reveal a non-linear trend indicating that bus-rail intermodal trips diminish as travel distance increases, with a concave contour of the sensitivity to walking distance. While distance-decay accessibility to rail transit has been analyzed by utilizing spatiotemporal big data, to the best of our knowledge, it has not been incorporated into a land use simulation process as an impact factor to examine the spatial heterogeneous effect of urban rail transit on land use changes.

2.3. Land use simulation: from raster-based to vector-based cellular automata models

Based on land or cadastral parcels, VCA models can more realistically reveal ground objects than raster-based models (Yao et al., 2017). Lu et al. (2020) proposed a VCA model that used land parcels as the basic analytical unit and compared its simulation results with a raster-based CA model. They concluded that the VCA model processed data faster and was more accurate for simulating urban land use changes compared to raster-based CA models (Barreira-González et al., 2015).

In the context of land use and transportation simulation, accessibility is identified as one of the main factors that drive land use changes. Accessibility plays a crucial role in connecting urban rail transit and land use (Liu and Zhu, 2004; Acheampong and Silva, 2015), as people usually travel to destinations that are more accessible. VCA models can better capture subtle urban land use changes related to human travel behavior and accessibility than raster-based CA models (Xu et al., 2022). Many studies have examined the accessibility factors in CA models, for example, proximity to different facilities (e.g., transportation nodes, educational facilities, and workplaces) (Campos et al., 2018; Silva et al., 2020). Most studies used Euclidean distance (measurement of linear distance) as accessibility to metro stations to simulate land use changes. However, these methods are incapable of accurately reflecting human movements because the travel frequency to rail transit usually decreases in a non-linear way (Ding et al., 2021). While several studies have examined the impact of rail transit as an important driver in simulating land use changes considering accessibility, few have analyzed the influence of rail transit accessibility on land use using VCA models considering non-linear distance-decay accessibility to metro stations.

3. Study site and data description

Shanghai is one of the largest metropolises in China and has one of the world's longest rail transit systems, which is a high-capacity public transportation. Based on the construction of rail transit, local governors in Shanghai have introduced the TOD concept into land use planning and adopted the TOD as a critical strategy to support sustainable urban development (Li et al., 2019). The guiding effect of rail transit on land use is more prominent in suburban areas than in central areas. In this study, Jiading New Town, a suburban new town in Shanghai, is chosen as the case study (Fig. 1). It is located 30 km from downtown Shanghai, with an area of 463 km^2.

In 2009, Jiading New Town became accessible to downtown Shanghai through Metro Line 11. By the year 2019, there were five metro stations in the area of Jiading New Town, associated with Metro Line 11. The study site was located at the end of Line 11, which connected Jiading New Town with downtown Shanghai.

Land use in Jiading New Town was influenced by the rail transit system. To simplify the initial dataset, we reclassified the land use data into six categories, including residential, administration and public services, industrial, commercial, non-development land use, and other land use. Industrial land had decreased by 20.0 % and commercial land had increased by 13.5 % from 2014 to 2019, according to the land use changes (Fig. 2), indicating an urban transformation that prioritized the tertiary industry.

Without the limitation of being locked to dock stations, the operation of a dockless bike-sharing system promotes the use of bike-sharing, reducing travel time to the metro station system, and thus improving the metro station accessibility. As of July 2017, Shanghai was the largest bike-sharing market worldwide with 1.5 million shared bikes in estimation (Zhang and Mi, 2018). As dockless bike-sharing has become an

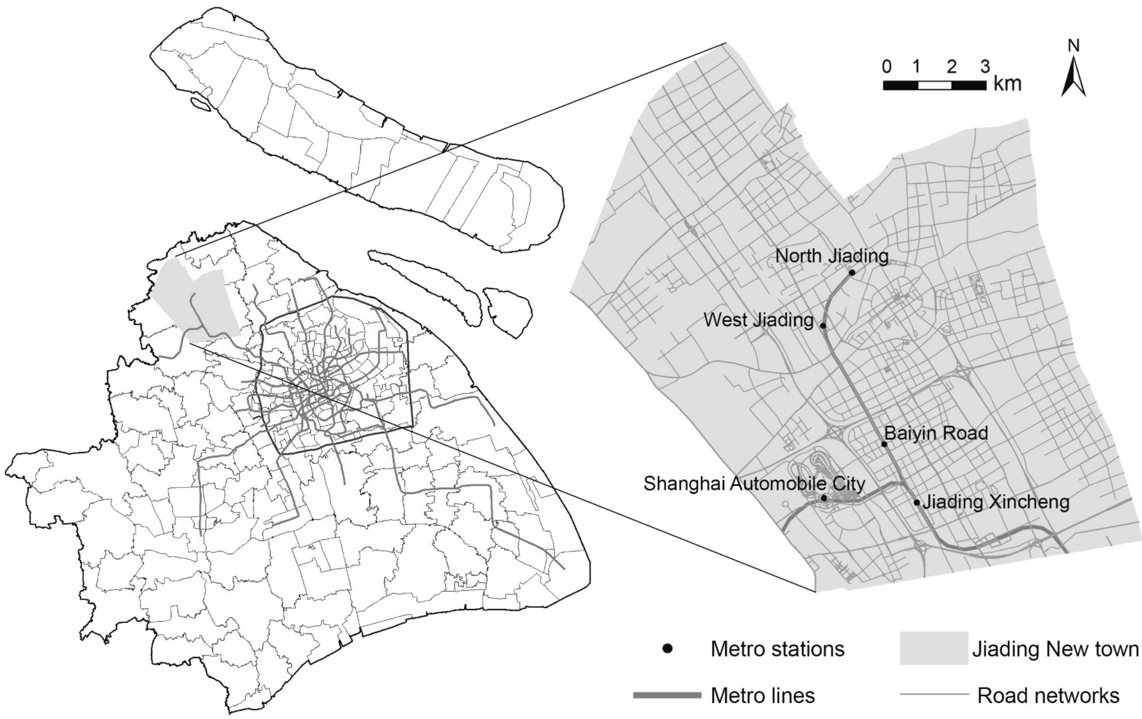

Fig. 1. Location of Jiading New Town (Shanghai, China) and the rail transit system.

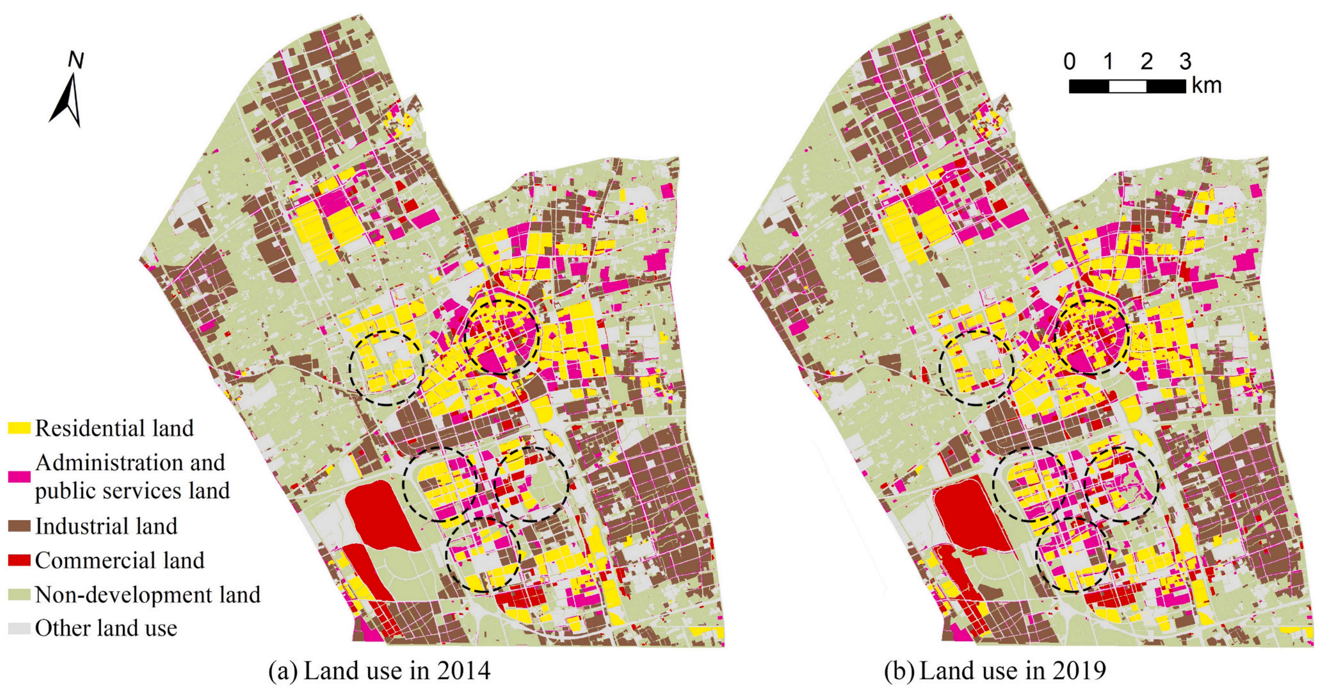

Fig. 2. Land use of 2014 and 2019 in Jiading New Town, Shanghai.
For better illustration, the circles in black highlight several areas with more land use changes.

important and effective way to solve the "first and last mile" problem around metro stations in recent years, it has amplified the TOD catchment areas to a certain extent.

In this study, bike-sharing trajectory data was used to calculate accessibility to metro stations. The bike trip trajectory dataset used in this study included 777,896 shared bike trips covering a period of two weeks. The dataset was provided by Mobike, which is the largest dockless bike-sharing service provider in China. As of 2017, Mobike's market share reached 56.56 %, approximately two times more than the second-ranked company ofo (29.77 %) (Sutu Institute, 2017). To identify bike trips that were connected to metro stations, a 50-m buffer around the station entrance/exit was defined as the connection range (Lin et al., 2019). Bike trip data with either the starting or ending points located within 50 m of metro stations were selectively extracted but both their starting and ending points within the 50-m range were removed. According to Zhang et al. (2019a), trips with a duration of fewer than 60 s or a length outside the range between 50 m and 5 km are considered outliers and removed. When dealing with bike trip trajectory data, besides using the shortest path algorithm to estimate the real paths for partially sampled data with only starting and ending points, resampling, stop point filtering, and map matching were used to estimate real paths from high-sampling but noisy GPS trajectories. Please refer to the work conducted by Zhang et al. (2019a) for more technical details.

4. Methodology

To study the impact of urban rail transit on land use changes, we developed a land use simulation model that considered the accessibility to metro stations, in a linear or non-linear scenario, as one of the driving factors in the land use simulation (Fig. 3). Based on historical land use data, we used the land use simulation model to simulate the land use changes in two scenarios, i.e., considering linear or non-linear distance-decay accessibility to metro stations.

In the linear distance-decay accessibility integrated land use simulation scenario, linear distance-decay accessibility to metro stations was incorporated as one of the driving factors in the land use simulation. First, the random forest model was used to mine the impact of various driving factors based on historical land use data, especially the accessibility to metro stations (Yao et al., 2017). Then, the coupled artificial neural network and cellular automata model were used to simulate the land use changes. Finally, the simulated land use was compared with the actual land use to assess the simulation accuracy in both scenarios considering linear and non-linear distance-decay accessibility.

The details about our methodology are introduced in the following sub-sections.

4.1. Accessibility to metro stations

The linear distance-decay accessibility to metro stations was based on Euclidean distance, while the non-linear distance-decay accessibility to metro stations was reflected by the frequency of shared bike-metro trips. They are separately discussed as follows.

4.1.1. Linear distance-decay accessibility to metro stations

The linear distance-decay accessibility to metro stations (A_{Linear}) was measured using Euclidean distance (measurement of linear distance) in the land use simulation process. As the distance to metro stations increases, accessibility to metro stations gradually decreases. Specifically, (A_{Linear}) was defined by Eq. (1) as follows:

$$A_{Linear} = \frac{Dist_{max} - Dist}{Dist_{max} - Dist_{min}} \quad (1)$$

Where *Dist* represents the distance from a parcel to the metro station, $Dist_{min}$ represents the minimum distance to the station among all surrounding parcels, and $Dist_{max}$ represents the maximum distance to the station.

4.1.2. Non-linear distance-decay accessibility to metro stations

The accessibility to metro stations in the land use simulation model was measured by travel frequencies in a bike-sharing context, as cycling was one of the main feeder modes used by passengers traveling to or from metro stations (Guo and He, 2020; Zhang et al., 2021). Bike-sharing trajectory data can be used to retrieve bike-metro feeder trips, calculate travel frequencies of these trips, and then delineate the accessibility in a non-linear distance-decay form. The exponential decay function has been used to reveal the relationship between travel distances and frequencies (Halás et al., 2014). Similarly, it was used to derive the non-linear distance-decay accessibility ($A_{Non-Linear}$), shown by Eq. (2) as follows:

$$A_{Non-Linear} = \alpha^{*} e^{-\beta^{*} Dist} \quad (2)$$

where *Dist* represents the distance to the observed metro station, $A_{Non-Linear}$ represents the travel frequency with a distance of *Dist*, α and β represent the distance-decay parameters.

The travel frequency decreases as the distance to metro stations increases, showing a non-linear distance-decay in willingness to travel.

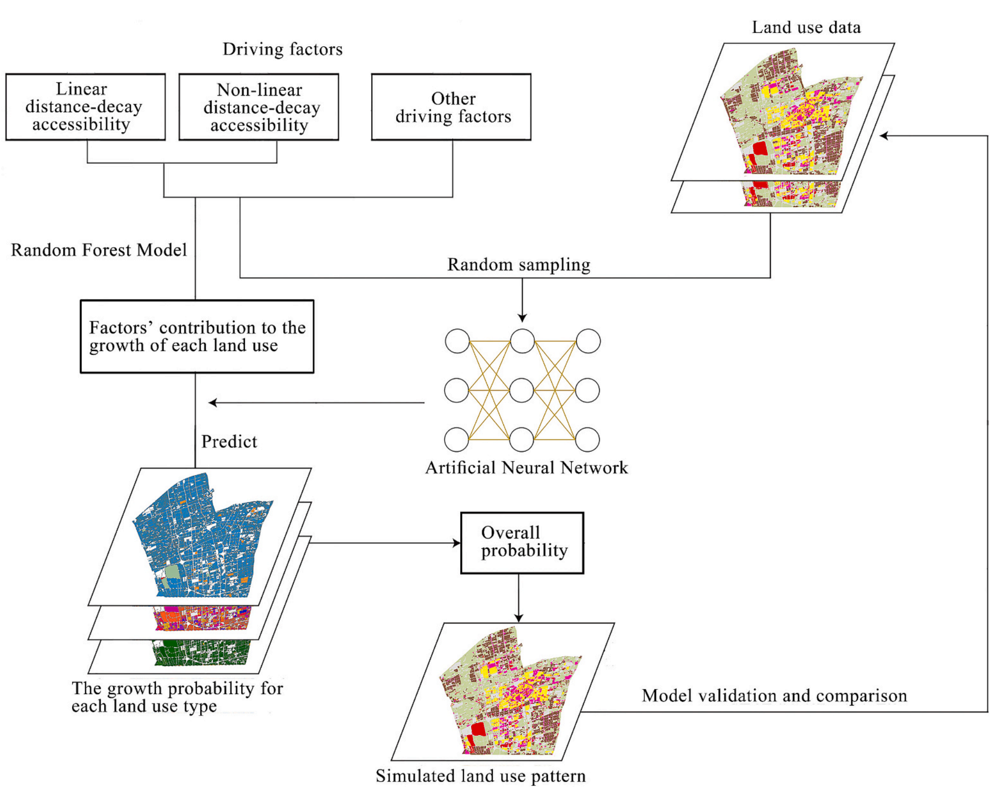

Fig. 3. The proposed vector-based cellular automata model considering linear or non-linear distance-decay accessibility to metro stations.

The parameter fitting results were $\alpha = 0.20$, and $\beta = 1.68$. The goodness of fit for the exponential decay function was 0.96 (Fig. 4).

Accessibility to metro stations based on linear or non-linear distance-decay functions was defined and visualized, separately (Fig. 5). In planning practice, we need to delineate the catchment area of a metro station, which is an easy-to-understand way to illustrate spatial boundary of the impact of rail transit on land use: the parcels inside the catchment area are often regarded as being greatly impacted by rail transit, while those outside the catchment area are assumed to be less impacted. By counting the cumulative percentages of bike-metro ridership by transfer distances, we delineated the impact area of metro stations. Via referring to previous studies (Lin et al., 2019), the 95th percentile value of the cumulative distribution of bike-metro feeder trip distance was used to determine the bike catchment area of metro stations. Based on bike-sharing trajectory data, the bike catchment area in this study was determined as the area within 2273 m of the metro station.

Earlier studies (e.g., Xu et al., 2022) confirmed the spatial heterogeneity of accessibility's impact on land use. Based on this, we further investigated the impact of linear and non-linear distance-decay characteristics of metro station accessibility on land use changes.

4.2. A vector-based cellular automata (VCA) model

As Jiading New Town experienced massive construction during the research period, the land use changes were significantly affected by transportation planning and economic growth. Table 1 shows the factors driving the land use transformations in the VCA model. These factors were categorized into three major categories, including transportation conditions, socio-economic conditions, and location factors.

Figure 6 shows the spatial distribution of driving factors. The *metro station accessibility*, indicating the impact of metro station accessibility on land use changes, was considered in both linear and non-linear scenarios. The *distance to main roads*, combined with the *metro station accessibility*, jointly reflected the transportation conditions, which would influence the land use changes especially those nearby. The *population density* is related to the intensity of metro station passengers, which influences the demand and distribution of land uses. Areas of high population density may require more residential and commercial facilities to meet the needs of residents. The *housing prices* reflect the evolution of residential land use values and influence changes in different types of land use according to the bid-rent theory. The *distance to Jiading New Town center* and the *distance to subcenters in Jiading New Town* are the location factors that significantly influence urban development. The six driving factors were imported into the VCA model to calculate the overall development probability. All the variables were normalized into the range of 0–1 in the land use simulation.

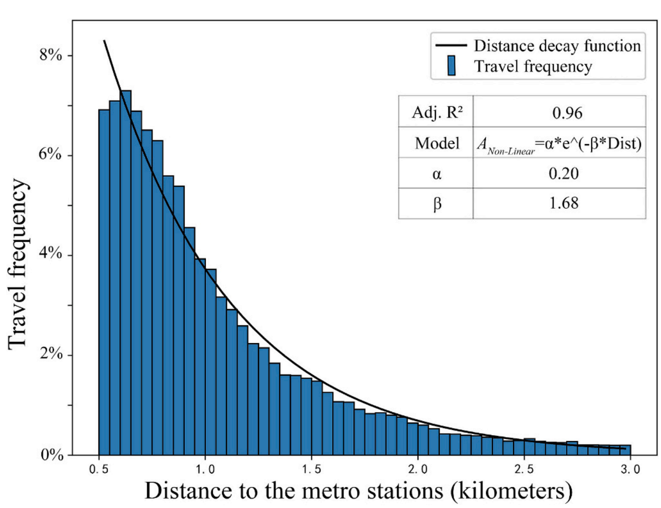

Fig. 4. Non-linear distance-decay accessibility ($A_{Non-linear}$) to the metro station.

The initial year of the land use data in this study was 2014, and the land use changes from 2014 to 2019 were simulated using the VCA model in the scenarios of considering non-linear and linear accessibility. According to Yao et al. (2017), the overall probability of land use changes for a parcel was derived by:

$$P_i^k = Pg_i^k \times \Omega_i^k \times Pr_i^k \times RA \times A_{k,i} \quad (3)$$

where k represents a land use type, i represents a land parcel, and P_i^k is the overall change probability. Pg_i^k is the overall development probability. Ω_i^k is the neighborhood effect, calculated based on the number and distribution of land use types within the surrounding parcels. Pr_i^k is the constraint factor limiting the development of water bodies and roads. Specifically, Pr_i^k is set to 0 for restricted development area and 1 for suitable development area. $RA = 1 + (-\ln y)^{\alpha}$ is the random factor, ranging between 0 and 1, where α is a parameter ranging from 0 to 1. $A_{k,i}$ is the accessibility to metro stations, which is introduced as a new component to derive the land use transition rule, because metro station accessibility is an important driving factor of land use changes. Accessibility to metro stations affects passengers' travel behavior causes spatial heterogeneity in the impact of urban rail transit on land use changes, and thus brings about land use changes eventually.

5. Results and discussions

5.1. Contributions of metro station accessibility

Contributions of the driving factors to land use changes were generated using the random forest model (Zhou et al., 2020), especially the impact of accessibility to metro stations on the growth of land parcels with various land use types. Fig. 7 indicates the extent of the impact of accessibility to metro stations on each intraurban urban land use type.

The contribution of metro station accessibility in the VCA model considering non-linear distance-decay was higher than that in the model considering linear distance-decay accessibility to metro stations. The contribution of non-linear distance-decay accessibility to metro stations for the administration and public services land use improved from 0.109 to 0.190, while the contribution for the commercial land use increased significantly from 0.137 to 0.175, and the contribution for the industrial land and residential land use also increased notably. These changes imply that the VCA model considering non-linear distance-decay accessibility to metro stations can more significantly reflect the driving role of the metro station accessibility in the process of land use changes. Metro station accessibility is an important factor because the metro is the most popular public transportation in Shanghai, and the operation of rail transit plays an important role in promoting land use changes. The development of rail transit attracts many people around the bike catchment areas, with the agglomeration of various economic activities, thus contributing to land use changes.

5.2. Simulation results and accuracy assessment

To clarify the land use simulation accuracy of the VCA model, the simulated land use results were compared with the actual land use within the bike catchment area (Fig. 8).

Two indicators, the overall accuracy (OA) and Figure-of-Merit (FoM) metric were used to assess the simulation performance of the model, shown as follows:

$$OA = 1 - \frac{A + C + D}{N} \quad (4)$$

$$FoM = \frac{B}{A + B + C + D} \quad (5)$$

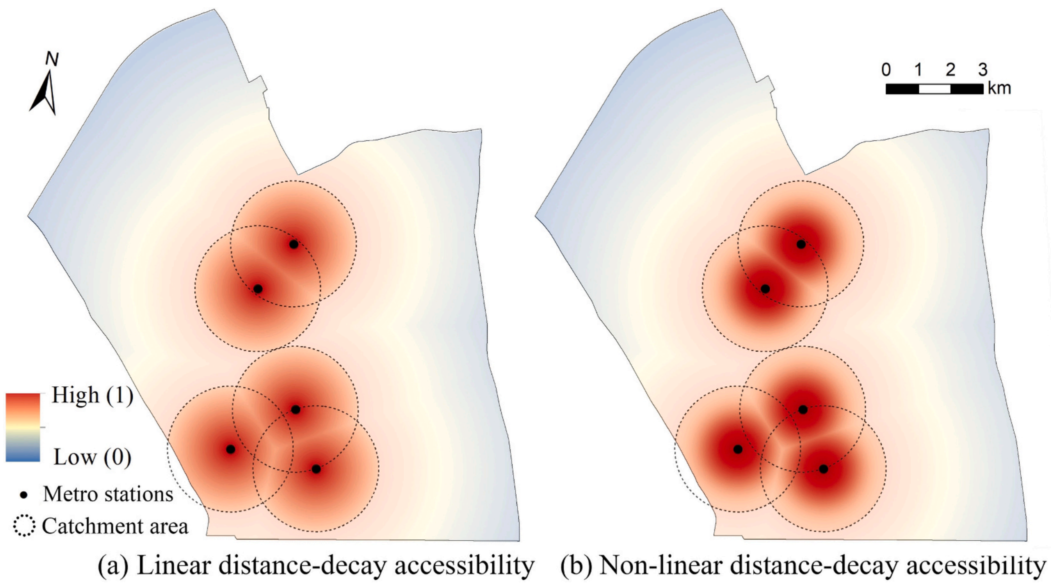

Fig. 5. Linear distance-decay and non-linear distance-decay accessibility to metro stations.

Table 1
List of driving factors used in the study.

Categories	Variables	Data source
Transportation conditions	Metro station accessibility	Metro stations data from Shanghai Metro official website (http://www.shmetro.com/)
	Distance to main roads	OpenStreetMap (https://www.openstreetmap.org)
Socio-economic conditions	Population density	WorldPop (https://hub.worldpop.org/)
	Housing prices	Second-hand housing transaction prices (http://www.soufang.cn)
Location factors	Distance to Jiading New Town center	OpenStreetMap (https://www.openstreetmap.org)
	Distance to subcenters in Jiading New Town	

Where A denotes a parcel that remains unchanged in simulation while in ground truth the parcel has changed; B denotes a parcel that correctly predicts a land-use change as well as the land-use type; C denotes a parcel that correctly predicts a land-use change however with a wrong land-use type; D denotes a parcel that has a land-use change in simulation while in ground-truth the parcel remains unchanged; and N represents the total number of cellular units in the study site.

Table 2 shows the overall performance of the simulation results. The overall accuracy was 0.739 for the land use simulation with linear distance-decay accessibility to metro stations and 0.752 for the non-linear distance-decay accessibility, with an improvement of 1.3 %. For the FoM measurement, the linear distance-decay accessibility integrated VCA model was 0.151 and the non-linear distance-decay accessibility integrated VCA model was 0.161, with a 1.0 % improvement. In the catchment area, the overall accuracy for the non-linear distance-decay accessibility integrated VCA model has reached 0.80, which is a 2.7 % increase compared to the linear model.

The results show that the non-linear distance-decay accessibility integrated VCA model had a significant improvement in accuracy over the linear distance-decay accessibility integrated VCA model within the station catchment area. The land use simulation which considers the non-linear distance-decay accessibility to metro stations had a higher FoM and overall accuracy than that considering the linear distance-decay accessibility to metro stations, indicating the advantage of cooperation of non-linear distance-decay accessibility to metro stations in simulating intraurban land use. In summary, the non-linear model, which considers the non-linear spatial heterogeneity of rail transit station accessibility, effectively improves the accuracy of land use simulation.

6. Conclusions

In conclusion, this study examined the spatial heterogeneity of metro station accessibility by using a non-linear distance-decay function calibrated from dockless bike-sharing trip data associated with bike-metro trips. By utilizing the non-linear distance-decay metro station accessibility as one of the driving factors in a vector-based cellular automata model, the simulation accuracy was higher compared to the model using linear distance-decay accessibility.

Previous studies mainly measured accessibility to metro stations by linear distance-decay function, which has ignored the non-linear distance-decay characteristics of the actual travel to the metro station. Bike-sharing has become an important and effective way to solve the “first and last mile” problem around rail stations in recent years. Bike-sharing trip data has a large volume and wide coverage, providing an opportunity to delineate the spatial heterogeneity of metro station accessibility. The non-linear distance-decay function of the bike-metro trips proposed in this study can better capture the spatial heterogeneity of the accessibility to metro stations than the linear distance-decay function.

The VCA model with non-linear distance-decay accessibility to metro stations can achieve a higher simulation accuracy compared to the model with linear distance-decay accessibility, and can better capture the impact of rail transit on land use changes considering the spatial heterogeneity of metro station accessibility. It reveals a non-linear relationship between rail transit and land use, indicating that rail transit exerts a substantial influence on land use. The combination of bike-sharing trip data and the VCA model can capture the spatial heterogeneous impact of the accessibility to metro stations on land use changes. This optimized model can be applied to other accessibility-related variables including bus stations and road network accessibility.

This study has potential practical implications for land use and rail transit planning when adopting transit-oriented development strategies. Firstly, leveraging big data for delineating catchment areas can help urban planners define the non-linear distance-decay to metro stations in the context of bike-sharing. Secondly, the heterogeneous impact of metro station accessibility on land use should be considered when

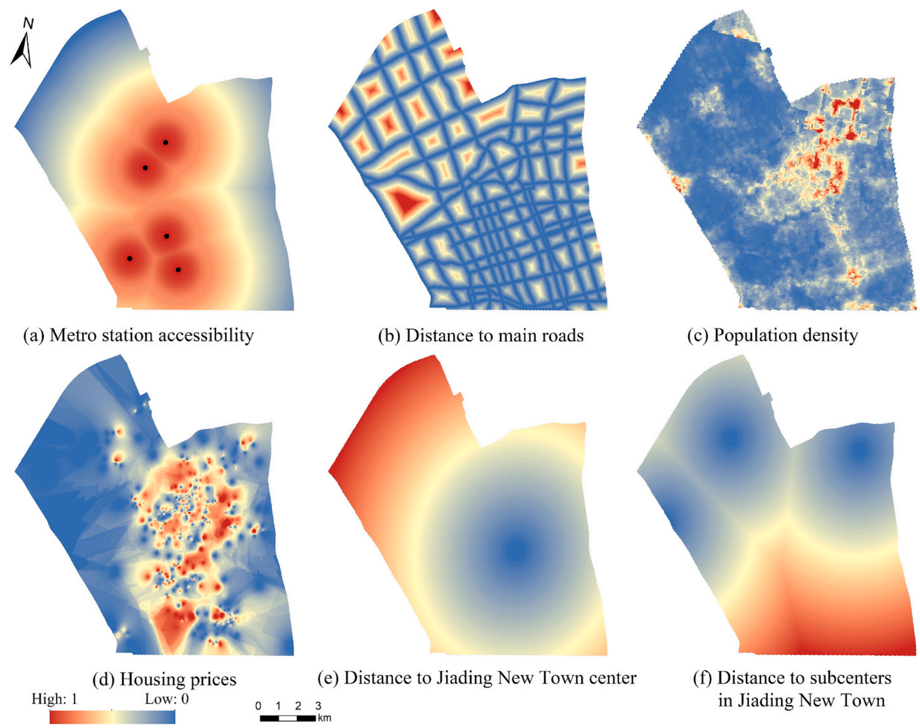

Fig. 6. Spatial distribution of driving factors.

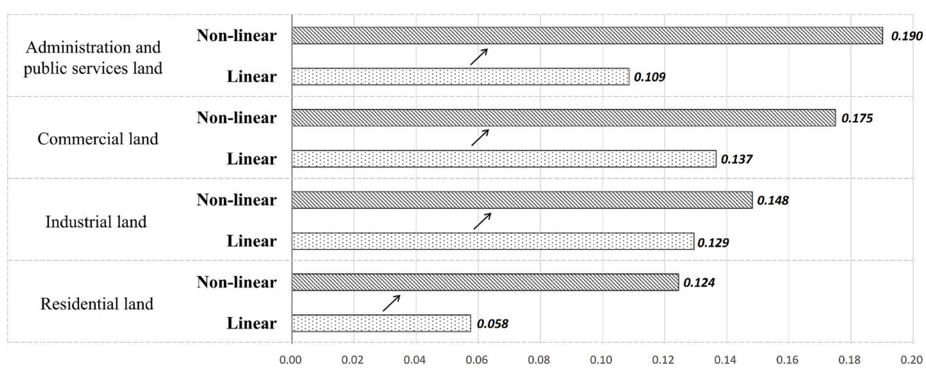

Fig. 7. Contributions of linear or non-linear distance-decay accessibility to metro stations for the growth of each intraurban land use type.

planning for different types of land use around metro stations. Lastly, our study demonstrates that a VCA model has the capability to simulate the heterogeneous impact of rail transit on land use changes, and thus has the potential to be applied in predicting land use changes around railway stations. Urban development around metro stations simulated by the VCA model could help optimize land use around metro stations and enable the formulation of more effective policies to encourage the collaborative development of urban rail transit and land use.

Several limitations need further consideration in future research. Firstly, this study only considers cycling in a bike-sharing context since it is an important non-motorized feeder mode, ignoring the accessibility of other feeder modes (e.g., buses, private vehicles). In our future study, it is valuable to obtain trajectory data of different feeder modes to capture the non-linear distance-decay accessibility to public transit systems. Utilizing multi-source datasets of different feeder modes to generate non-linear distance-decay functions with different parameters might enhance the credibility of the land use simulation model. Secondly, although we have selected the best-performing parameters after parameter adjustments based on previous research (Yao et al., 2024), combining multiple neighborhood strategies and iteration times with in-depth sensitivity analyses might improve the reliability of the VCA model as well. This can help us have a more comprehensive understanding of the complex relationships between transportation and land use. Thirdly, the reliability of this research may also be affected by using the bike-sharing data from only one company. The distributions of geofences and bikes vary across service providers, resulting in diverse use patterns of shared micromobility. Therefore, it is valuable to obtain more representative data from several companies to achieve a comprehensive estimation of the spatial heterogeneity of urban expansion around metro stations. Finally, this study may not fully represent the diversity of geographical characteristics in different cities. Therefore, it is imperative to expand the case studies from different cities to enhance the robustness of the study. Future research would focus on further refining the model to enhance its performance.

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Fig. 8. Enlargement of actual (a) and simulated land use with linear distance-decay (b) and non-linear distance-decay (c) accessibility to metro stations.

Table 2
The overall performance of the simulation results.

Land use simulation model	Overall accuracy	Figure-of-Merit
Linear distance-decay accessibility integrated VCA	0.739	0.151
Non-linear distance-decay accessibility integrated VCA	0.752	0.161
Improvement of accuracy	1.3 %	1.0 %

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CRediT authorship contribution statement

Xingang Zhou: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Zhouye Zhao:** Writing – original draft, Methodology, Formal analysis, Data curation. **Wenyan Fu:** Writing – original draft, Data curation. **Zhengdong Huang:** Writing – review & editing, Writing – original draft. **Yao Yao:** Writing – review & editing, Writing – original draft. **Yongqiao Huang:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Yongping Zhang:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis.

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.

Data availability

The authors do not have permission to share data.

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