Frontiers of Architectural Research 12 (2023) 291—307

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.keaipublishing.com/foar

RESEARCH ARTICLE

Metropolitan spatial structure analysis based on the identification of commuting zones with Nanjing City as an example

Yan He, Xiao Wu*, Linjin Wang

School of Architecture, Southeast University, Nanjing, 210096, China

Received 3 May 2022; received in revised form 15 September 2022; accepted 14 October 2022

KEYWORDS
Commuting center;
Commuting zone;
Urban space;
Cellular signal data;
Nanjing

Abstract Commuting zone research is critical to the understanding of the operational rules of the metropolitan spatial structure and improving spatial performance. This study aims to identify the main commuting centers and zones by using cellular data with Nanjing City as the example. This study analyzes the operational features of the internal spatial structures of the city from two dimensions by merging multi-source data, namely, commuting centers and zones, thus achieving an understanding of the existing problems with the urban spatial structures and their internal causes. Results showed that the commuting zones of Nanjing are distributed in a pattern of "multiple commuting centers", with Xinjiekou—Hunan Road and Hongwu Road—Chaotiangong—Shuangtang as the core, Mochou Lake as the main commuting area, and Dongshan and Jiangpu as the secondary commuting zones. Significant differences and similarities are discovered in our comparisons along the two dimensions of commuting zones and centers in terms of spatial structural factors, such as land use, transportation, and commuting in the city. The similarity is shown as a common declining trend in the values of all our indicators with the increase in the distance of commuting zones from the city center. However, the differences are significant in terms of the clustering features of the various parameters concerning commuting centers and zones. Specifically, four clustering patterns are discovered, namely, "monocentric clustering", "circular monocentric clustering", "polycentric clustering", and "sparsely dotted distribution". This study sheds light on the existing problems with the city's spatial structure and proposes some overall suggestions toward urban spatial structure improvement on the basis of these findings.

* Corresponding author.
E-mail address: 2265884125@qq.com (X. Wu).
Peer review under responsibility of Southeast University.

https://doi.org/10.1016/j.foar.2022.10.002

1. Introduction

Urban spatial structure is the manifestation of how the physical environment, functional activities, and cultural values of a city relate to each other, and the quality of urban spatial structures affects the realization of urban functions (Zhou and Ye, 2013). The identification of urban spatial structure could greatly contribute to the research into the internal development mechanisms and the improvement of the spatial performance of a city. "Urban spatial structure" has long been a topic of great interest in several fields, such as economy, demography, urban planning, and geography. Many scholars have performed extensive studies on the identification of urban spatial structures from different perspectives. For example, scholars have carried out studies from the perspective of urban spatial forms to analyze urban spatial structures, central systems, and impact factors by utilizing land use, building attributes, luminous intensity, premature ovarian insufficiency (POI) intensity, and other data (Liu et al., 2015; Chen et al., 2016; Luo and Li, 2019; Wu et al., 2020; Zhang et al., 2017). Other scholars have conducted research from the perspective of population scale to explore urban residence—work space relations, employment center systems, and urban public activity centers based on resident population, employment, and recreation data (Liu and Liu, 2018; Liu et al., 2018; Shi et al., 2017; Niu et al., 2014). Meanwhile, other scholars conducted research from the perspective of transportation and commuting to identify the polycentric forms and functions of cities using data on density of transportation facilities, density of road networks, records of smart cards (used in taking buses or the subway), questionnaires, and cellular data (Zhang et al., 2017; Burger and Meijers, 2012; Guo et al., 2016, 2019).

Among these studies, research on urban spatial structure from the perspective of transportation and commuting has achieved richer findings. These studies, which primarily identify urban spatial structures using data from transportation facilities and questionnaires, have shown the following characteristics: in terms of research content, these studies focused on identifying the polycentric structure and urban center systems of the cities in question, followed by an in-depth interpretation of their formation mechanisms. With regard to research methodology, some of these studies were conducted to identify urban spatial structures by using transportation and road network data. Such studies are characterized as studies of urban spatial structure as a manifestation of static physical space, indicating that they cannot accurately reflect the distribution features of real population activity space (Ding et al., 2019). Other studies analyzed the clustering rules of urban spaces using individual data, such as bus smart card, metro smart card, and taxi traffic data. These studies could accurately manifest individual movement and urban space utilization. However, these studies were unable to present the full spectrum of characteristics of urban spatial structure because they concentrated on the public transportation population. Nevertheless, other studies use questionnaires and census data to identify urban spatial structures. The availability and timeliness of such data are poor. Moreover, the continuity of these studies is frequently compromised by administrative division, resulting in the inability to reflect the rules of spatiotemporal urban population changes in an accurate and real-time manner. In comparison with the first three research methods, the mobile phone signaling data of individuals cover every mobile phone holder; it no longer relies on sampling with small sample sizes and can effectively shift to reflect the general spatiotemporal patterns. Meanwhile, mobile positioning data, as a type of dynamic data, reveal the spatial location of mobile phone holders in real-time, allowing the spatiotemporal dynamics of an individual's employment, recreation activities, residence, and other activities to be described. On this basis, mobile phone signaling data are characterized by good spatiotemporal accuracy, extensive coverage, and timely updates. The bottom-up research mechanism studies the macro state of cities from a micro perspective, presents the influence of individual acts on the overall pattern, and minutely identifies the urban spatial structure. However, such studies are relatively few, particularly those in relation to analyzing the operational patterns of urban spaces by using mobile phone signaling data to identify commuting zones.

The preceding review indicates that the characteristics of urban spatial structures could be analyzed from a variety of perspectives, including urban morphology, economic population, public facilities, and transportation and commuting. The interpretation of urban spatial structures from the perspective of transportation, especially through commuting zones, is the most unique among these studies. Commuting zones are the space scope formed by the activity paths of urban commuting population, which could well reflect the spatial structure and functional zoning of a city. Just as the functional layout characteristics of a metropolis could decide the distribution of its commuting space to a certain degree and even the formation of the commuting zones, the distribution of commuting space can influence the operational rules of urban space as a whole. In conclusion, commuting zones and urban spatial structure are closely connected. This study is conducted to identify the major commuting centers in Nanjing (as an example) using cellular signal data. On this basis, the commuting zones of the city are recognized, and the internal features of commuting zones and their relationship with the urban spatial structure in combination of multi-source data are analyzed from two dimensions, namely, commuting centers and zones, thus proposing optimization strategies for improving the city's spatial performance.

The remainder of this work is organized as follows: Section 2 provides the literature review. Section 3 presents the research methodology. Section 4 demonstrates the analysis of the research findings from two dimensions. Section 5 is the research discussion.

2. Relevant literature

2.1. Relevant research progress

Urban spatial structure has long been a topic of profound research interest in disciplines, such as urban planning and geography. The major methods and data available for the study of urban spatial structure from the perspective of transportation include the following: transportation facility density data, road network density data, public transportation data, individual commuting questionnaires, census data, and cellular signal data.

Some studies use transportation facility density and road network density data to identify urban spatial structure and assess urban spatial performance from the perspective of accessibility (Sun et al., 2013; Ding, 2010). Other studies combine transportation facility density data with other multi-source data, such as nighttime light brightness data and land attributes, to measure the urban structures of various factors, thereby reflecting a city's polycentric characteristics and clarifying its rules of spatiotemporal evolution (Zhang et al., 2017). Certain studies used a combination of road network and POI data to identify the polycentric spatial structures of cities and compare and analyze the various component spaces in terms of clustering levels and hierarchical differences (Mao et al., 2019).

The data mainly used in public transportation include taxi passenger flow data, bus smart card data, and metro smart card data. Liu et al. (2015) and Guo et al. (2016) proposed a method for identifying the multiple centers of a city based on taxi passenger flow data to analyze the relationship between these urban centers and the functions of their hinterland. Wei et al. (2020) clarified the characteristics of resident travel and urban spatial structure by utilizing taxi GPS tracking big data. Zhong et al. (2014) and Sun et al. (2015) used data on commuting by bus and rail transportation in their study of the relationship between the work—home space of urban residents and urban functions, showing how the opening of subways lines enhanced the stability of urban space. Long et al. (2012) analyzed the work—home spatial structure of Beijing using bus smart card data. Zhang et al. (2018) analyzed the urban spatial structure of Singapore using a combination of bus smart card data and taxi tracking data. The study suggested that different types of geographic big data could lead to the delineation of various urban spatial structures and discovered that urban spatial structure generated using taxi tracking data is more stable and compact.

Traditional questionnaire surveys and population census data are more commonly used in individual commuting and population census. Meng and Chen (2006) summarized the spatial structural patterns of commuting in Shanghai and clarified the relationship between these patterns and commuting distance by analyzing the basic features of commuting travel behaviors of residents in the city. Zhou and Yan (2006) and Jiang and Wu (2009, 2013) studied the characteristics of work—home space of residents in Guangzhou by using the fifth population census data and resident travel data. The study provided insights into the dynamic evolutionary process of urban physical spaces by analyzing the commuting patterns and their changes.

In response to the limitations of the above-mentioned research methodologies, cellular signal data have been widely utilized in the studies of urban spatial structure due to their satisfactory spatial temporal accuracy, great coverage scope, and fast update speed. For example, cellular signal data were used in the research to identify the place of employment or work of the employed (Shi et al., 2017), and the employment density information acquired was further used in the identification of urban employment centers, their energy level, and the hinterland and sphere of influence of each center. Niu et al. (2014) used cellular signal data from different time periods in a day to determine the level of urban public centers and their functional types (Ding et al., 2016). Yang et al. (2018) focused their study mainly on how commuting behavior could influence urban spatial structure and identified 13 commuting spatial communities in Shenzhen, all of which had a polycentric internal structure. Zhou et al. (2016) studied the dynamic changes of the urban spatial structures of Shenzhen in the different time periods of a day by using cellular signal data and clarified how population movement could affect urban spatial structure. According to the study, the changes in the nature of activity conducted by the population in different time periods are the most significant driver of changes in urban spatial structure. Cellular data have been used as the primary component in the identification of urban spatial structure. However, existing studies mainly focused on the analysis of the characteristics of commute travel and the interrelation between commuting and urban spatial environment. Few studies have delved further into the relationship between the spatial characteristics and components of commuting zones or the relationship between commuting zones and urban spatial structure. Only the following studies were conducted on urban spatial structure from the perspective of commuting zones. Niu et al. (2014) delineated commuting zones of Shanghai based on the number of commuters working in its urban downtown area during daytime and nighttime using cellular data. With these commuting zones as the scope closely connected with Shanghai's downtown area, the spatial scope of the city proper of Shanghai was re-defined and zoned. Guo et al. (2019) further studied the relationship between commuting zones and their component elements and the relations between commuting zones, metropolitan spatial structure, and spatial performance. Given that these studies are mostly set in metropolitan cities, such as Shanghai and Beijing, this study takes Nanjing as an example to address this gap. This study also employs mobile phone signaling data to identify the spatial structure of commuting centers and commuting zones in Nanjing from the perspective of human activities. Furthermore, this study analyzes the correlation between intrinsic composition and the spatial structure of the city at the two-tier scale of "commuting centers—commuting zones". Specifically, this study will answer the following questions: how jobs are distributed and which areas have the highest employment density. The commuting centers can be identified, and the differences in land use, transportation, and level and distribution of job-housing factors between every center can be understood based on the answers.

2.2. Relevant concepts

Commute refers to the regular travel between two places, including going to work, going to school, and other travel activities. Several types of commute are available, both temporally and spatially. For example, some people work only in the afternoon, while others work only at night. Some individuals may work for 2 days and rest on the third day. To simplify the study, the commute here is defined as commute on an 8 h workday to a fixed place of stay, which is the most common prevalent type of commute (Ding et al., 2019). Commuting centers are areas formed in people's commute travel, which have a higher density of employment activities and cover a larger area. Commuting centers function as important nodes in the urban commuting network (Ding et al., 2019). Commuting zones are defined (Guo et al., 2016; Lu et al., 2020) as sets of spatial scope for the purpose of completing specific commute travel, with commuting centers as the core. Moreover, commuting zones are identified mainly to evaluate the intensity of connection between urban employment centers and their surrounding areas in terms of commute and transportation.

Commuting zones are not only areas with high intensity of urban land use and high concentration of urban factors but also areas with the most prominent intensity and demand of urban activities. The study of urban commuting zones, the assessment of the spatial concentration level and hierarchical differences of different factors in these zones, and the establishment of the distribution of every occupational center in a city are critical to guiding the development and regulation of planning of urban spatial structures.

3. Research design

3.1. Data sources and cleaning

This study collected cellular signal data for 2 weeks during November 2015 (including ten weekdays and two weekends). Each piece of signal data contains an anonymous user number, a time stamp, and a base station number among other information. An average of 100 million users' signal data are generated every day and collected in the city proper, totaling approximately 1.4 billion records. The positions of these users are identified through 46,000 base stations, making such data relevant in the identification of commuting zones.

This study also uses multi-source data, including land use data, POI data of service facilities, house price data, bus and subway station data, bicycle sharing stand data, and so on. Such a type of data is used for the analysis of the internal characteristics of commuting zones.

3.2. Research approach

This study takes Nanjing as an example and identifies its major commuting centers and commuting zones using cellular data. Thereafter, this study analyzes and evaluates the spatial structural characteristics of these commuting zones from two dimensions, namely, commuting zones and centers, in combination with multi-source data. The research approach is specified as follows (Fig. 1):

(1) Cellular signal data were used to identify the commuting population of the city according to the daily commuting routine of urban residents. The commuting population served as an indicator in the density and local space auto-correlation analysis, thus identifying commuting zones on a certain scale.
(2) The employed population ratio was used to identify the commuting zones of Nanjing, with the commuting centers as the core. Specifically, the ratio of commuting population traveling to the commuting centers from other parts of the city was calculated.
(3) On this basis, multi-source data were used to analyze the characteristics of the internal structures among the urban spatial structure from two dimensions, namely, commuting centers and zones. The specific urban spatial factors involved include land use, transportation, and commuting. The three indicators used in the analysis of land use are degree of mixed land use, service POI density, and house price information. Two indicators, namely, transportation accessibility and bicycle sharing trajectory, were used in the analysis of the transportation element. Two indicators, namely, average commuting distance and degree of work—home separation, were used in the analysis from the commuting perspective. In this part of the study, the calculation unit for all indicators, except for the two indicators of POI and sharing bicycle trajectory, shall be Thiessen polygons.
(4) This study summarized the operational rules of the urban spatial structures and existing problems with these structures based on the findings acquired from the above analyses of internal urban spatial factors from the two dimensions. Moreover, this study further proposes optimization strategies for the operations of metropolitan spatial structures.

3.3. Identification of place of residence and employment

Based on the above-mentioned research approach, this study identified the place of residence and employment of cellphone users through their cellular signal data. The identification process is as follows. The cellular signal data of two consecutive weeks were first cleaned for redundant data, and the trajectory sequence data were marked out. The frequency with which a cellphone user appeared in the same place was calculated, whereby the user's travel trajectory was mapped out. The user's places of residence and employment were identified based on the results. The specific identification process was borrowed from previous studies (Yan et al., 2018). Finally, the data of one particular weekday was selected as the data source, which means that the places of employment of around 1.7 million users and residence of approximately 3.33 million users were identified out of the 100 million users. Approximately 1.18 million users with employment and residence locations identified were selected as the principal commuting population in this study. The identification results are shown in Fig. 2.

To verify the accuracy of the above-mentioned identification method, the Spearman's correlation coefficient was used to test the linear correlation between the cellular signal data and the permanent resident population, as shown by the population census. According to the calculation, the two factors were positively correlated, with the correlation coefficient being 0.84. The result is more satisfactory compared with the findings of similar studies. The accuracy in identifying the place of employment could not be verified at the current stage due to the unavailability of the original economic census data to the public.

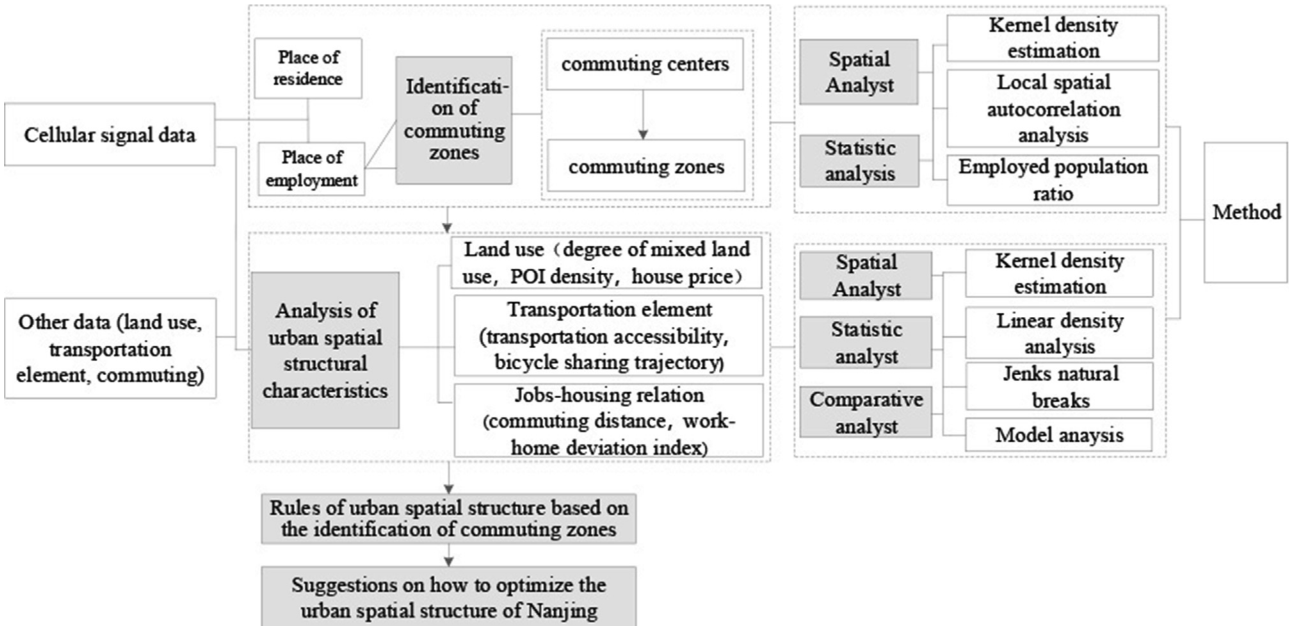


Fig. 1 Framework of this study.

3.4. Identification of commuting zones

The commuting zone in this study refers to the sets of spatial scopes for the purpose of completing specific commute travel, with commuting centers as the core. The commuting centers should be first determined before identifying the commuting zones (Fig. 3). The specific process is as follows:

(1) Identification of Commuting Centers

First, kernel density estimation was used to calculate the population density. With 800 m taken as the search radius,[i] density calculations were carried out according to the number of users connected to each base station (Niu et al., 2014). Thus, the users' spatial distribution density results were acquired and plotted using a 200 m × 200 m grid.

Next, local G statistics (Getis-Orid Gi*) for local spatial autocorrelation analysis was used to conduct a spatial clustering analysis in terms of density. The areas with a significance level of 5% and a Z value of over 1.96 were taken as the high-value clustering zones.

Finally, the Jenks natural break classification system was used to classify the population density into five ranks, thus obtaining the spatial distribution density of the commuting population. The commuting centers were determined in view of the density and total volume of the commuting population through the local spatial autocorrelation analysis. Referring first to Shanghai and Wuhan and the definition of employment centers (the employment density of such a center in Shanghai shall exceed 12,700 employees/km^2, and that in Wuhan shall exceed 10,700 employees/km^2) and considering the population scale of Nanjing, this study identified five commuting centers with an employment density of over 10,000 people/km.[2] Finally, these commuting centers were ranked from strong to weak according to their strength and sphere of influence: Xinjiekou—Hunan Road > Hongwu Road—Chaotiangong—Shuangtang > Mochou Lake > Dongshan > Jiangpu.

(2) Identification of the Commuting Zones based on the Commuting Centers

This study adopted the employed population ratio method by drawing on the definition criterion of metropolitan areas in Japan (Wei and Zhao, 2005). According to this criterion, if more than 10% of the workers and students over the age of 15 from a permanent residence city—town—village (equivalent to a town in China) of a city commute to the downtown area for work and school, then that city—town—village falls within the city's metropolitan area. Specifically, regions of such city—town—village comprise the scope the city's metropolitan area. In Japan, metropolitan areas are determined based on commuting workers and students, indicating that metropolitan areas are also commuting zones or areas. Given that this method has been used by other scholars in China to

[i] Spatial distribution characteristic of base stations in cities: In the city center, the coverage of base stations is 500 m in radius. In and beyond suburban areas, the coverages of base stations are 500—1000 and above 1000 m in radius. Considering the coverage of base stations in cities (500—1000 m in radius) and the average distance between base stations, the 800 m search radius is taken as the final basis for the calculations in this study.

[ii] In terms of calculation for the degree of mixed land use, with the Thiessen polygon derived from each base station as the calculation unit, the land use type within an area in the original formula is replaced with the total number of land use types within the coverage of a base station in this study. The closer the degree of mixed land use is to one in value, the more diversely used the land within the coverage of a certain base station is.

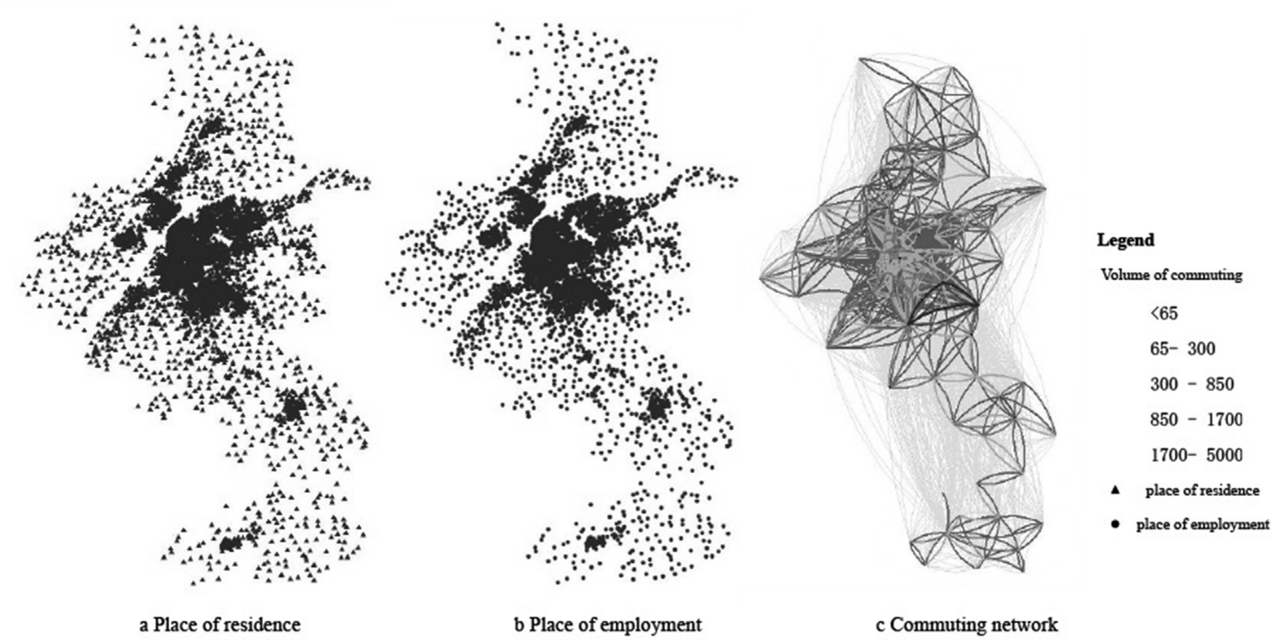


Fig. 2 Identification of residential and employment location and internal commuting network.

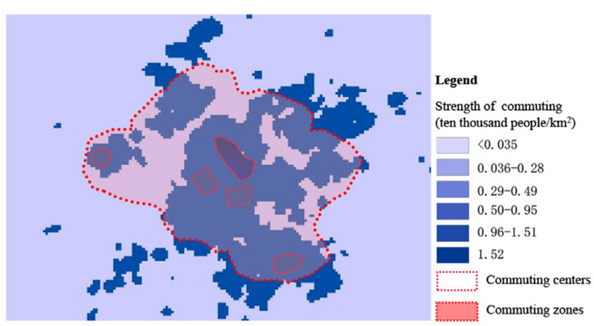


Fig. 3 Identification of commuting zones and centers.

identify commuting zones of Shanghai (Ding et al., 2019), this study applied the same method to identify the commuting zones of Nanjing. The specific process is as follows. The ratio of people commuting from a surrounding street to the aforementioned street to the total population of the surrounding street was calculated, with the street in which a commuting center is located as the center. Streets with a commuting population ratio greater than 10% were selected, and commuting zones were delineated based on the boundaries of these streets. Finally, all commuting zones of Nanjing were mapped out.

4. Analysis of urban spatial structural characteristics based on the identification of commuting zones

The internal components of a commuting zone include land use, transportation environment, commuting, and socio-economic factors. To prevent wide time differences between other multi-source data and mobile phone signaling data, which would easily increase the analysis bias, the time difference between the two sources should not exceed 3 years (e.g., point of Interest and housing price information data used in this study were sourced from 2017, and land use mix, transport accessibility, and bicycle sharing data were obtained from 2018). Land use factors are measured using the three indicators of degree, namely, mixed land use, service POI density, and house price information. Transportation environmental factors are measured using the two indicators of transportation

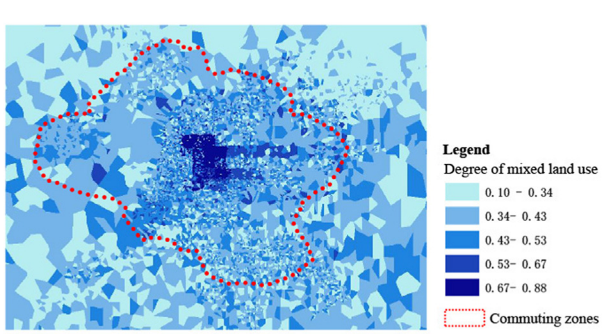


Fig. 4 Degree of mixed land use in the commuting zones.

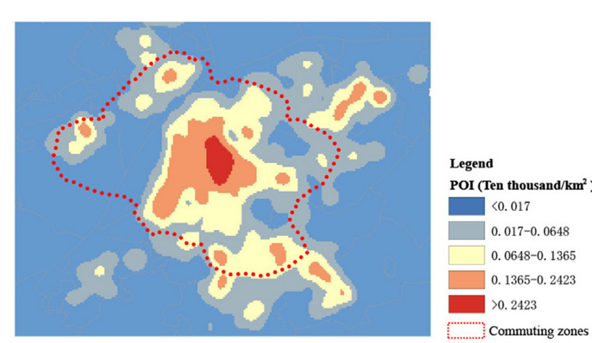


Fig. 5 Service facility POI density in the commuting zones.

accessibility and bicycle sharing trajectory. Socio-economic factors are measured using the two indicators of job—housing ratio and house price. Commuting factors are measured using the two indicators, namely, average commuting distance and degree of work—home separation. All the analyses were conducted from two dimensions, namely, commuting centers and zones. In this study, the calculation units for all indicators were Thiessen polygons, except for the two indicators of POI and sharing bicycle trajectory.

4.1. Characteristics of the land use factor

The land use factor was analyzed mainly by the three indicators of degree of mixed land use, service facility density, and house price from the two dimensions. The degree of mixed land use was calculated using a formula (Guo et al., 2019) from a previous study as follows[ii]:

$$H = -\sum_i P_i \times \ln(P_i)/\ln(I),$$

where P_i refers to the ratio of i type of land use in the area, and i refers to the total number of land use types in the area. The value range of H is 0—1. The closer H is to one, the more diverse the land use is.

Service facility POI density was calculated through kernel density estimation, typically with an 800 m search radius (Chen et al., 2016; Shi et al., 2017).

The spatial distribution rules concerning the housing price information were acquired using the Jenks natural break classification method. The dual-scale analysis results of the three indicators are shown in the diagrams and tables below.

(1) Characteristics of the land use factors in the commuting zones

In the commuting zones (Fig. 4), mixed land use is characterized by "**monocentric clustering**", that is, a high degree of mixed land use is typically observed in the central areas of the commuting zones, specifically Xinjiekou, Hunan Road, and Hongwu Road. The median-value areas are connected to each other inside the commuting zones, covering a great area. The low-value areas are small in area and scattered in the north of the commuting zones (the high value is greater than 0.53, the median value is 0.43—0.53, and the low value is less than 0.43).

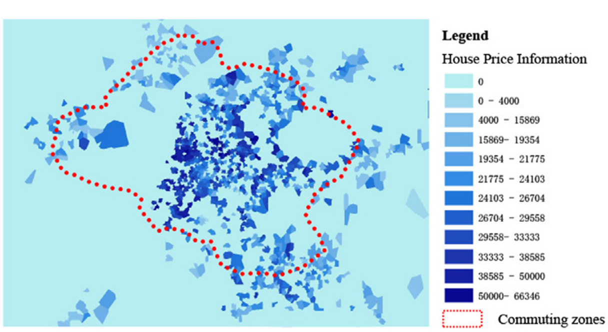


Fig. 6 Distribution of house price information in the commuting zones.

In the commuting zone (Fig. 5), service facility POI density presents the characteristic of "**circular monocentric clustering**". Areas with a high service facility density include the traditional downtown area with Xinjiekou as the center, Dongshan in the south, and Jiangpu in the northwest. The areas with a median service facility density are huge in size and located in the fringes of the downtown area. Meanwhile, the areas with a low service facility density are small in size and mostly concentrated in Jiangpu in the northwest (the high value is greater than 0.1365, the median value is 0.0648—0.1365, and the low value is less than 0.0648).

In the commuting zones (Fig. 6), house prices present a "**polycentric clustering**" distribution. High prices (more than RMB 30,000/m^2) are mainly concentrated in the main urban area. The median-value areas are large in size and connected to each other on the periphery of the main urban area and around the commuting zones. The low-price areas are small in size and scattered in the west (the high value is greater than RMB 33,333/m^2, the median value is RMB 21,775—33,333/m^2, and the low value is less than RMB 21,775/m^2).

(2) Characteristics of the land use factors in the commuting centers

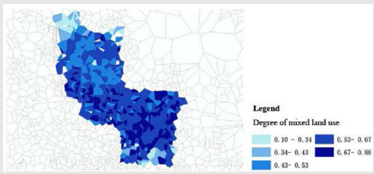
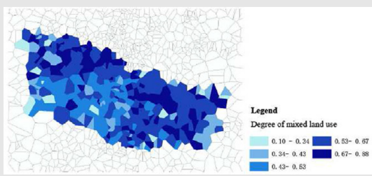
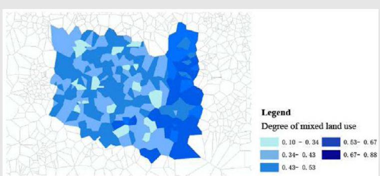
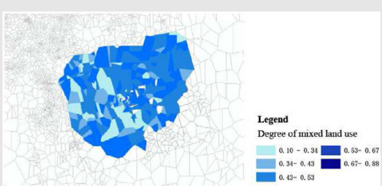
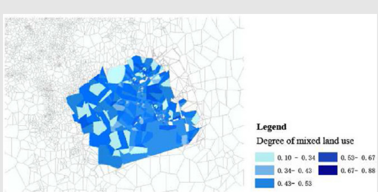
The characteristics of mixed land use of the five commuting centers (Xinjiekou—Hunan Road, Hongwu Road—Chaotiangong—Shuangtang Road, Mochou Lake, Dongshan, and Jiangpu) are shown in Tables 1—3.

4.2. Characteristics of the transportation environmental factors

A dual-scale analysis of the transportation environmental factors was conducted relying mainly on the two indicators of transportation accessibility and shared bicycle trajectory. Of the two indicators, transportation accessibility provided an overall evaluation of accessibility in three aspects: bus, subway, and road network on the basis of the available data. Bus accessibility was obtained by calculating the 500 m coverage of a bus stop, subway accessibility was determined by calculating the 800 m coverage of a subway station, and road accessibility was calculated by calculating the 1 km coverage of a road (Wei and Zhao, 2005). The total weight of the three factors was taken as the transportation accessibility[iii] and calculated according to the following formula.

[iii] Transportation accessibility is an overall assessment of accessibility by bus, subway, and road networks. Accessibility by bus is calculated with the coverage of bus stations being 500 m in radius, by calculating the ratio between the 500 m coverage area of a bus station and the area of a commuting zone. Accessibility by subway is calculated with the coverage of subway stations being 800 m in radius by calculating the ratio between the 800 m coverage area of a subway station and the area of a commuting zone. Accessibility by road is calculated with the coverage of road being 1000 m in radius by calculating the ratio between the 1000 m coverage area of a road and the area of a commuting zone. The total of the three values is the transportation accessibility.

Table 1 Degree of mixed land use of the commuting centers.

Commuting Center	Characteristics of mixed land use of the commuting centers
	Xinjiekou commuting center presents a "contiguous patch distribution pattern" in terms of the degree of mixed land use. The areas with a high degree of mixed land use cover almost the entire commuting center, with areas of a low degree of mixed land use being narrow and small and mainly scattered in the north.
	Hongwu Road commuting center presents a "contiguous patch distribution pattern" in terms of the degree of mixed land use. The areas with a high degree of mixed land use are large in size and connected to each other in the southeast. Meanwhile, the areas with a low degree of mixed land use are relatively small in size and located in the southwest.
	Mochou Road commuting center presents a "dot-based distribution pattern" in terms of the degree of mixed land use. The areas with a high degree of mixed land use are narrow and small in size and mainly scattered in the east. Meanwhile, the areas with a low degree of mixed land use are relatively large in size and connected to each other in patches.
	Dongshan commuting center presents a "scarcely dotted distribution pattern" in terms of the degree of mixed land use. The areas with a high degree of mixed land use are narrow and small in size and located in the east. Meanwhile, the areas with a low degree of mixed land use are relatively large in size and connected to each other in patches in the northwest.
	Jiangpu commuting center presents a "scattered polycentric distribution pattern" in terms of the degree of mixed land use. The areas with a high degree of mixed land use are narrow and small in size and mainly concentrated in the southeast. Meanwhile, the areas with a low degree of mixed land use are relatively large in size and connected to each other in patches in the northwest.

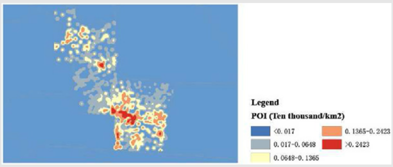
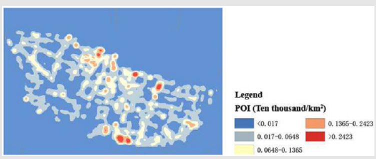
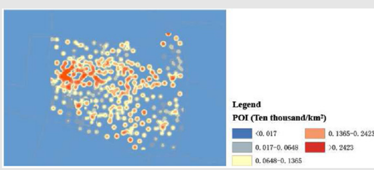
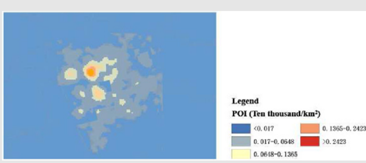
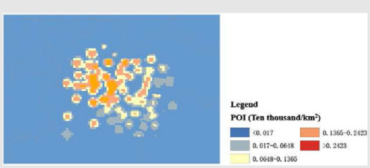
Transportation accessibility = 1/3 × (fraction of 500 m bus coverage) + 1/3 × (fraction of 800 m rail coverage) + 1/3 × (fraction of 1000 m road coverage).

The analysis of bicycle sharing trajectory relied on the simulation and estimation of the traveling trajectory. First, the sharing bicycle data were obtained, which consisted of a unique individual-wise code, the coordinates of the starting and end points of an individual ride, bike riding speed, and so on. Thereafter, the coordinates of the starting and end points are inputted in the open-source platform Amap, through whose route planning function the bike riding trajectory was simulated in combination with the road network data. Given the universal application of the route planning function of Amap for bike riders, this simulated path was taken as the actual traveling trajectory of a user. Finally, the traveling trajectories of all sharing bicycle users obtained in the same manner were subjected to a density analysis. The specific analysis results are shown in the following diagrams and tables.

(1) Characteristics of the transportation environmental factors in the commuting zones

In the commuting zones (Fig. 7), transportation accessibility is characterized by a "circular monocentric clustering pattern". The areas with a high transportation accessibility are mainly concentrated in the traditional downtown area, specifically areas around Xinjiekou, Hunan Road, and Hongwu Road. Meanwhile, the areas with a low transportation accessibility are mainly located in the fringes of commuting

Table 2 Service facility POI density diagrams of the commuting centers.

Commuting Center	Characteristics of service facility POI density diagrams of the commuting centers
	Xinjiekou commuting center presents a "**relatively agglomerated polycentric linkage distribution pattern**" in terms of service facility POI. The areas with a high density are mostly concentrated in the south and sometimes scattered in the north. Meanwhile, the areas with a low density are located in the middle.
	Hongwu Road commuting center presents a "**scarcely dotted distribution pattern**" in terms of service facility POI. The areas with a high density are relatively small in size and mostly concentrated in the middle and north. Meanwhile, the areas with a low density are relatively large in size and connected to each other in patches in the east, west, and south.
	Mochou Road presents a "**contiguous patch distribution pattern**" in terms of service facility POI. The areas with a high density are relatively large in size and connected to each other in patches in the west and middle. Meanwhile, the areas with a low density are relatively small in size and mainly concentrated in the east and south.
	Dongshan commuting center presents a "**scarcely dotted distribution pattern**" in terms of service facility POI. The areas with a high density are narrow and small in size and mainly concentrated in the middle. Meanwhile, the areas with a low degree of mixed land use are relatively large in size and connected to each other in patches.
	Jiangpu commuting center presents a "**polycentric clustering pattern**" in terms of service facility POI. The areas with a high density are relatively large in size and mainly concentrated in the middle. Meanwhile, the areas with a low degree of mixed land use are relatively large in size and mainly concentrated in the south.

zones. Specifically, transportation accessibility declines as the commuting zones stretch outward.

In the commuting zones (Fig. 8), sharing bicycle trajectory is characterized by a "**polycentric clustering pattern**". The areas with a high density of bike riding trajectory are mainly concentrated in four commuting centers, namely, Xinjiekou, Hongwu Road, Mochu Lake, and Dongshan. Meanwhile, the areas with a low density of bike riding trajectory are mainly located in the west of the commuting zones.

(2) Characteristics of the transportation factors of the commuting centers

The characteristics of the transportation factors of the five commuting centers, namely, Xinjiekou–Hunan Road, Hongwu Road–Chaotiangong–Shuangtang Road, Mochou Lake, Dongshan, and Jiangpu are shown in Tables 4 and 5.

4.3. Characteristics of the commuting factors

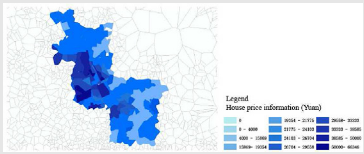
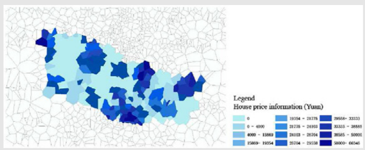
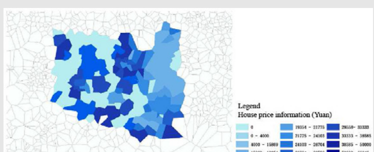
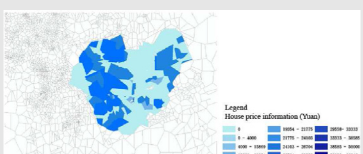
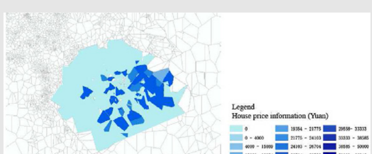
The work–home spatial characteristics of the commuting zones and centers are assessed using the two indicators of average commuting distance and work–home deviation.

Commuting distance is obtained in the following manner. After the commuting distance of the residents on each Thiessen polygon (total distance between the place of residence and place of work of all residents) was identified, the average commuting distance of each polygon was derived as per the total number of residents identified on each polygon. The formula for calculating commuting distance d is as follows:

$$d = R \cdot \arccos[\cos Y1 \cdot \cos Y2 \cdot \cos(X1 - X2) + \sin Y1 \cdot \sin Y2],$$

where R refers to radius of earth (6371.0 km); ($X1$, $Y1$) indicate the longitude and latitude of the place of

Table 3 House price diagrams of the commuting centers.

Commuting Center	Characteristic of house price diagrams of the commuting centers
	Xinjiekou commuting center presents a **"circular monocentric clustering pattern"** in terms of house price. The areas with high-value house prices (greater than RMB 30,000/m^2) are mainly concentrated in the middle. The other areas boast mostly median-value (RMB 20,000—30,000/m^2) house prices, with nearly no low-value areas in this commuting center.
	Hongwu Road commuting center presents a **"dot-based distribution pattern"** in terms of house price. The areas with high-value house prices are relatively small in size and mainly located in the west and north. Meanwhile, the areas with low-value house prices are relatively great in size and connected to each other in patches in the southwest.
	Mochu Road commuting center presents a **"polycentric clustering pattern"** in terms of house price. The areas with high-value house prices are relatively small in size and mainly located in the middle. Meanwhile, the areas with median-value house prices are greatest in size and connected in patches in the east. The areas with low-value house prices are also large in size and mainly concentrated in the west.
	Dongshan commuting center presents a **"scarcely dotted distribution pattern"** in terms of house price. Areas with high-value house prices are smallest in size and scattered in the west. The areas with median-value house prices are relatively small in size and connected in patches in the west. The areas with low-value house prices are the largest in size and connected to each other in contiguous patches in the middle.
	Jiangpu commuting center presents a **"scarcely dotted distribution pattern"** in terms of house price, with areas with high-value house prices scattered in middle and those with median-value house prices mainly concentrated in the west. The areas with low-value house prices are the largest in size and connected to each other in contiguous patches.

residence, respectively; ($X2$, $Y2$) indicate the longitude and latitude of the workplace, respectively; $X1$ and $X2$ refer to the longitude; and $Y1$ and $Y2$ represent the latitude.

The degree of work—home deviation index is calculated by using a method proposed in a previous study (Guo et al., 2019), and the specific formula is as follows[iv]:

$$SD=\left|\left(\frac{\text{Employed population}}{\text{Employed population in the zone}}\right)\times\left(\frac{\text{Residential population in the zone}}{\text{Residential population}}\right)-1\right|,$$

where the SD-value shows the degree of match between a residential space and a work space. The greater SD-value is, the worse the match.

(1) Characteristics of the commuting factors in the commuting zones

In the commuting zones (Fig. 9), the average commuting distance presents a **"scarcely dotted distribution pattern"**. The high-value (greater than 15 km) areas are the smallest in size and mainly scattered in the center and periphery of the commuter zones. The median-value (5—15 km) areas are relatively small in size and connected to each other in patches. The low-value areas are the greatest in size and also connected to each other in patches.

[iv] In terms of calculations for the degree of work-home deviation in the paper, with the Thiessen polygon derived from each base station as the calculation unit, the degree of work-home deviation equals the absolute value of the employed population to resident population ratio minus one. This value indicates the match between the residential space and work space. The greater the value, the worse the match.

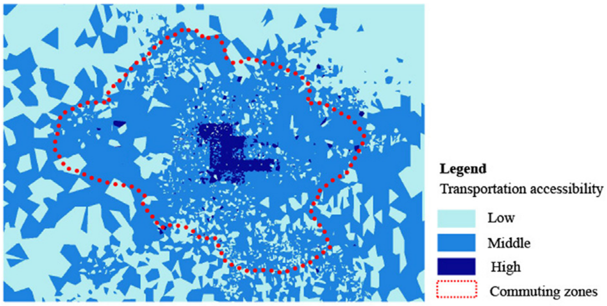


Fig. 7 Transportation accessibility of the commuting zones.

In the commuting zones (Fig. 10), the degree of work—home deviation presents a **"scarcely dotted distribution pattern"**. The high-value (>1.0) areas are the smallest in size and scattered in the northeast. The median-value (0.3—0.5) areas are the greatest in size and mainly concentrated in the middle of the commuting zones. The low-value (<0.3) areas are scattered in the periphery of the commuting zones.

(2) Characteristics of the commuting factors of the commuter centers

The characteristics of the commuting factors of five commuting centers, namely, Xinjiekou, Hongwu Road, Chaotiangong—Shuangtang Road, Mochou Lake, and Jiangpu, are shown in Tables 6 and 7.

5. Conclusions and discussion

The analysis based on mobile phone signaling data essentially examines the urban spatial structures from the perspective of transport demand. Furthermore, the identification of commuting zones and the evaluation and analysis of the components of the commuting zones can provide a reference for extensively understanding the evolution of the internal spatial structure of a city, revealing the driving mechanism of urban development and the rational organization of urban structure. This study aims to identify the commuting centers and zones in Nanjing by using cellular data. Moreover, this study analyzed the operational features of the internal spatial structures of the city from two dimensions, namely, commuting centers and zones, in combination with multi-source data, to draw conclusions about their internal causes. The discussions and conclusions are specified as follows.

5.1. Discussion: suggestions on how to optimize the urban spatial structure of Nanjing

According to the research findings, in the operations of Nanjing's urban spatial structure, Xinjiekou—Hunan Road, Hongwu Road—Chaotiangong—Shuangtang, and Mochou Lake commuting centers in the main city are highly clustered in terms of land use and the transportation environment, whereas the other commuting zones are not significantly clustered or agglomerated. In particular, the three major commuting centers of Dongshan and Jiangpu in the sub-city present the lowest degree of clustering. Moreover, the degrees of clustering in terms of all factors decline with the increase in distance from Xinjiekou, which was taken as the core, demonstrating the operational features of urban spaces of a monocentric city. However, the spatial characteristics of the commuting zones in terms of commuting factors present a completely opposite distribution pattern, with commuting factors scarcely scattered in the main city and relatively clustered in the sub-city. Specifically, the areas located farther away from the main urban area display a higher degree of work—home separation and a greater commuting distance. This situation compromises the operating efficiency of the urban spaces to a certain

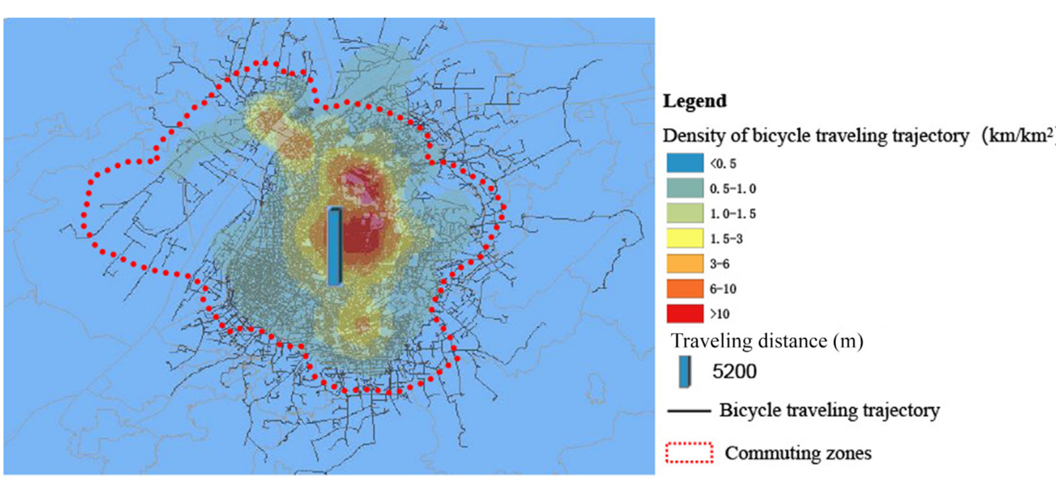
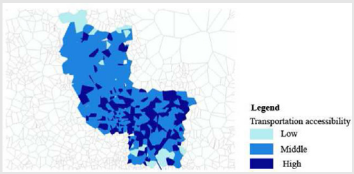
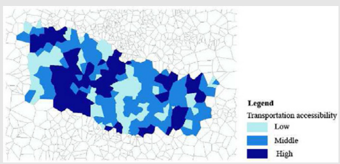
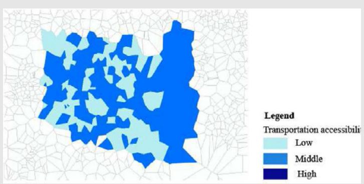
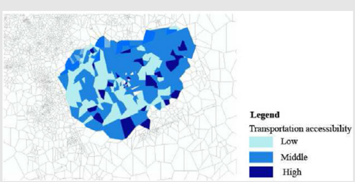
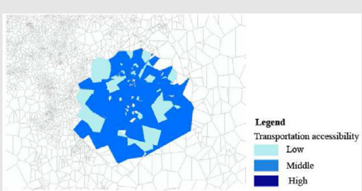


Fig. 8 Sharing bicycle traveling trajectory diagram.

Table 4 Transportation accessibility of the commuting centers.

Commuting Center	Characteristics of transportation accessibility of the commuting centers
	Xinjiekou commuting center is characterized by a "**polycentric clustering pattern**" in terms of transportation accessibility. The areas with a high accessibility are mainly concentrated in the middle. The median-value areas are connected to each other in patches in the north, and low-value areas are scattered in the far north and south.
	Hongwu Road commuting center is characterized by a "**contiguous patch distribution pattern**" in terms of transportation accessibility. The areas with a high accessibility are concentrated in the northwest and east. The median-value areas are mainly concentrated in the west and south. Meanwhile, the low-value areas are scattered in the south.
	Mochou Road commuting center is characterized by a "**dot-based distribution pattern**" in terms of transportation accessibility. The areas with a high accessibility are scattered in the east. The median-value areas are clustered in the west and east with multiple centers. Meanwhile, the low-value areas are clustered in the south and north with multiple centers.
	Dongshan commuting center is characterized by a "**scarcely dotted distribution pattern**" in terms of transportation accessibility. The areas with a high accessibility are scattered in the southeast. The median-value areas are relatively large in size and connected to each other in patches in the north, while low-value areas are mainly concentrated in the west.
	Jiangpu commuting center is characterized by a "**dot-based distribution pattern**" in terms of transportation accessibility. The areas with a high accessibility are scattered in the middle. The median-value areas are clustered in the middle, south, and northeast with multiple centers. Meanwhile, the low-value areas are scattered in the northwest.

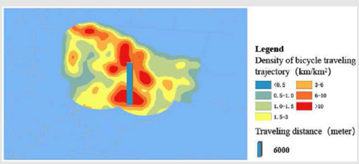
extent. Given this situation, suggestions concerning the layout of the various spatial factors in the commuting zones and centers are proposed as follows.

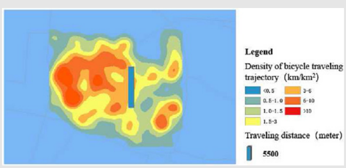
(1) From the land use factor, the entire commuting area presents a monocentric clustering pattern in terms of the degree of mixed land use and service facility POI. Specifically, the three major commuting centers are highly clustered in terms of land use and service facilities. Consequently, the three major commuting centers have excessively-concentrated resources and population and show an imbalance between supply and demand. Meanwhile, the sub-city only scarcely scatters land use factors and lacks appeal to the employed population, making it unable to relieve the spatial pressure of the main city.

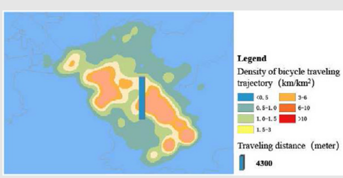
This imbalance is attributed to the development mode of a monocentric urban spatial structure, which easily results in the significantly different distribution of resources from the main urban area to the periphery. According to the city's overall plan, Nanjing is upholding a spatial strategy for urban space development with the downtown area as the core, while developing gradually to sub-cities, such as Dongshan in the south, Xianlin in the east and Pukou in Jiangbei. Given this plan, this study suggests that the spatial layout of land use factors across

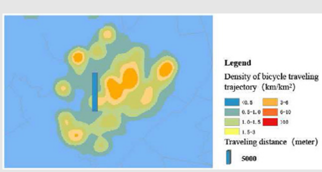
Table 5 Sharing bicycle trajectory of the commuter centers.

<table>
<tr><th>Commuting Center</th><th>Characteristics of sharing bicycle trajectory of the commuter centers</th></tr>
<tr><td>


</td><td>Xinjiekou commuting center is characterized by a "polycentric clustering pattern" in terms of sharing bicycle trajectory. The areas with a high linear density (marked in red) are mainly concentrated in the middle and south. Meanwhile, the median and low value areas are scattered in the north.</td></tr>
<tr><td>


</td><td>Hongwu Road commuting center is characterized by a "polycentric clustering pattern" in terms of sharing bicycle trajectory. The areas with a high density are concentrated in the middle and north. Meanwhile, the median and low value areas are relatively small in size and scattered in the west and east.</td></tr>
<tr><td>


</td><td>Mochou Road commuting center is characterized by a "circular polycentric clustering pattern" in terms of sharing bicycle trajectory. The areas with a high density are relatively large in size and connected to each other in patches in the in the middle and west. Meanwhile, the median and low value areas are relatively small in size and scattered in the southeast.</td></tr>
<tr><td>


</td><td>Dongshan commuting center presents a "dual-core clustering pattern" in terms of sharing bicycle trajectory. The high-value areas are located respectively in the west and southeast. Meanwhile, the median and low value areas are relatively large in size and mainly concentrated in the north and south.</td></tr>
<tr><td>


</td><td>Jiangpu commuting center presents a "monocentric clustering pattern" in terms of sharing bicycle trajectory. The high-value areas are small in size and mainly concentrated in the north. Meanwhile, the median value areas are large in size and connected to each other in patches. Moreover, the low value areas are relatively large in size and scattered in the fringes.</td></tr>
</table>

the entire commuting area be adjusted from the current "monocentric clustering" pattern to a "polycentric clustering" pattern. The degree of mixed land use and service facility density in the three commuting centers of the sub-cities (Dongshan and Jiangpu) shall be enhanced, and a differentiated mode of mixed land use shall be implemented in the main city and sub-cities. In the main city, proximal distribution of commerce, public services, offices, and residential buildings shall be promoted, thus facilitating a polycentric clustering mode. In the sub-cities, commerce, residential areas, and public services shall be proximally distributed, while industry, residential areas, and commerce shall be separated from each other, laying them out in groups.

(2) According to the analysis of the transportation environmental factors, significant differences could be observed across the commuting zones in terms of transportation accessibility. The areas with a high level of transportation accessibility are mainly located in the downtown area, while sub-cities are relatively poorly accessible. On the one hand, this situation results in a low transportation connectivity between the main city and sub-cities, hence the strong spatiotemporal limitations to residents' travel across the main city and sub-cities. On the other hand, residents of the sub-cities are also faced with spatiotemporal restrictions even when traveling inside the area, hence a low traveling efficiency.

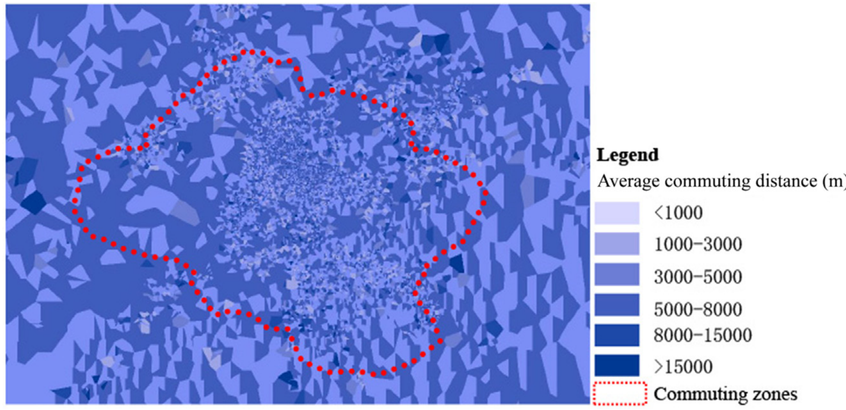


Fig. 9 Average commuting distance of the commuting zones.

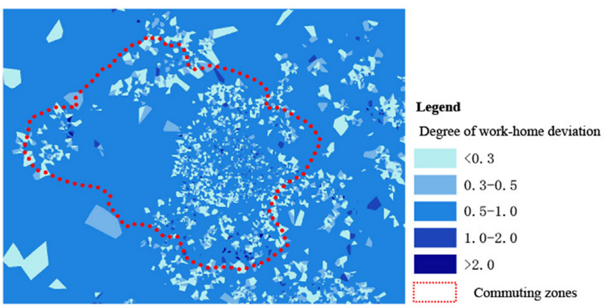


Fig. 10 Degree of work-home deviation of the commuting zones.

The primary cause for these differences lie is that buses, subway, sharing bicycles, and road network are densely allocated in the main city, but far less so in the sub-cities. Moreover, subway lines and roads connecting the main city to sub-cities are also low in density. According to Nanjing's transportation plan, it will build an urban transportation framework "led by rail transits and guided by two expressways" in the future. Four passenger flow corridors of rail transits have been formed in the main city based on this plan and viewed from the commuting zones as a whole. Accordingly, the connection between buses, bicycles, and motor vehicles and the rail transit stations must be enhanced by setting up bus stations, bicycle, and car parking lots around the rail transit stations. As regards the sub-cities, more efforts should be exerted into increasing the number of bus routes than that of roads. This study also suggests that rail transits and expressways between the main city and the sub-cities must be constructed to ensure that the transportation connection between the main city and sub-cities could be enhanced. A land use layout with rail transits as the focus shall be built in the main city, given the clustering of commercial, business, and residential buildings here. Meanwhile, rail transit stations shall be closely connected to buses and bicycles to satisfy residents' needs for seamless transfer in their travels to work and other destinations. As regards the sub-cities that focus more on industry rather than residence or commerce, bus routes between land used for different purposes shall be opened, and bicycle parking lots shall be set up around bus stations to ensure that a public transportation network oriented toward buses and supported by bicycles could be formed to satisfy residents' need for short-distance travel. In addition, the number of urban roads shall be moderately increased to facilitate residents' long-distance travel.

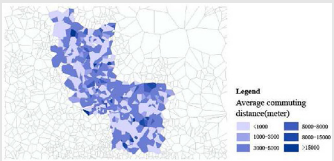
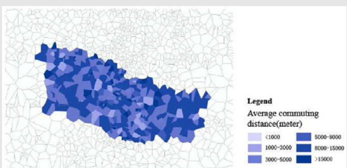
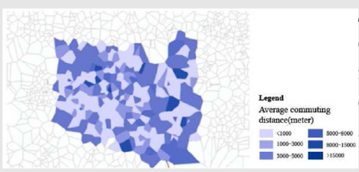
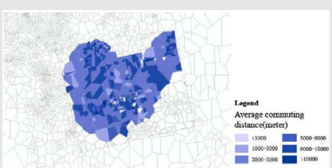
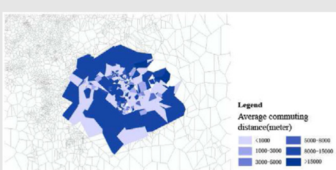
5.2. Conclusions: rules of urban spatial structure based on the identification of the commuting zones

(1) The commuting zones of Nanjing are found to be distributed in a pattern featuring "five major commuting centers"—with Xinjiekou—Hunan Road, Hongwu Road—Chaotiangong—Shuangtang as the core, and Mochou Lake as the main commuting areas, and Dongshan and Jiangpu among the commuting zones.

(2) The following specific findings have been obtained in the analysis of the characteristics of internal urban spatial structures from the two dimensions of commuting zones and commuting centers using multi-source data. From the land use factors, the degree of mixed land use and service facility POI presents an overall "monocentric clustering" pattern in the commuting zones. A declining trend could be observed in the diversity of land use and service facility POI as the scope of the commuting zones stretches outward. Meanwhile, house price distribution presents a "polycentric clustering" pattern. From the five major commuting centers, the degree of mixed land use is found to be distributed either in a "contiguous patch", "contiguous patch distribution pattern", or "scarcely dotted" pattern. Service facility POI density presents a "polycentric clustering" distribution pattern, and house prices demonstrate either a "polycentric clustering" or a "scarcely dotted" distribution pattern.

(3) From the transportation factors, transportation accessibility in the commuting zones presents a

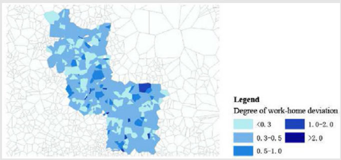
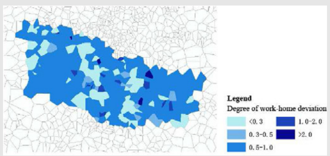
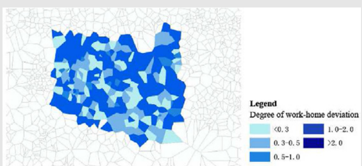
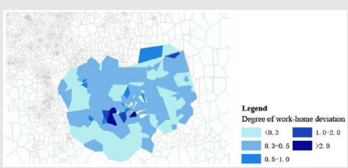
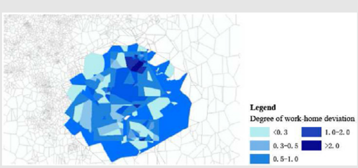
Table 6 Average commuting distance of the commuting centers.

Commuting Center	Characteristics of average commuting distance of the commuting centers
	Xinjiekou commuting center presents a "**contiguous patch distribution pattern**" in terms of average commuting distance. The high-value areas are small in size and scattered in the periphery. The median-value areas are relatively large in size and connected to each other in patches in the middle. The low-value areas are relatively small in size and concentrated in the east and west.
	Hongwu Road commuting center presents a "**scarcely dotted distribution pattern**" in terms of average commuting distance. The high-value and low-value areas are narrow and small in size and scattered in the periphery. Meanwhile, the median-value areas are the greatest in size and connected to each other in patches.
	Mochou Road commuting center presents a "**scarcely dotted distribution pattern**" in terms of average commuting distance. The high-value areas are narrow and small in size and scattered in the periphery. The median-value areas are relatively large in size and mainly concentrated in the north. Meanwhile, the low-value areas are also relatively large in size and connected to each other in patches.
	Dongshan commuting center presents a "**polycentric distribution pattern**" in terms of average commuting distance. The high-value areas are narrow and small in size and mainly scattered in the east and west. The median-value areas are scattered in the middle, while low-value areas are narrow and small in size and scattered in the middle.
	Jiangpu commuting center presents a "**dual-core clustering pattern**" in terms of average commuting distance. The high-value areas are relatively large in size and connected to each other in patches in the north and south. The median-value areas are scattered in the middle, while low-value areas are concentrated mainly in the northwest.

"circular monocentric clustering" pattern. Transportation accessibility declines as the scope of the commuting zones stretches outward. Bicycle sharing trajectory presents a "dual-core clustering" pattern, with a high trajectory density mostly concentrated in the center of the commuting zones. From the five major commuting centers, the transportation accessibility presents either a "polycentric clustering" or a "scarcely dotted" distribution pattern, while the bicycle trajectory demonstrate a "polycentric clustering pattern" in terms of density.

(4) From the commuting factors, the commuting zones present a "scarcely dotted distribution pattern" in terms of average commuting distance. The areas with a great commuting distance scarcely dot the middle and periphery of the commuting zones, while the other areas have either a median or short commuting distance. The degree of work—home deviation in the commuting zones also displays a "scarcely dotted distribution pattern", with areas featuring work—home deviation scattered in the northeast and other areas manifesting work—home balance. From the five major commuting centers, the average commuting distance and the degree of work—home deviation present either a "polycentric clustering" or "scarcely dotted" distribution pattern.

Table 7 Degree of work—home deviation of the commuting center.

Commuting Center	Characteristics of work—home deviation of the commuting center
	Xinjiekou commuting center presents a "**scarcely dotted distribution pattern**" in terms of the degree of work—home separation. The high-value areas are scattered in the periphery. The median-value areas are the greatest in size, covering almost the entire commuting center, while the low-value areas are narrow and small in size and mainly concentrated in the north.
	Hongwu Road commuting center presents a "**dual-core clustering pattern**" in terms of the degree of work—home separation. The high-value areas are scattered in the west and east. The median-value areas are the greatest in size and connected to each other in patches in the south, west and north. Meanwhile, the low-value areas are relatively small in size and mainly concentrated in the middle.
	Mochou Road commuting center presents a "**scarcely dotted distribution pattern**" in terms of the degree of work—home separation. The high-value areas are narrow and small in size and scattered in the periphery. The median-value areas are relatively great in size and mainly concentrated in the east and west with multiple centers. Meanwhile, the low-value areas are scattered in the middle and in the south.
	Dongshan commuting center presents a "**monocentric clustering pattern**" in terms of the degree of work—home deviation. The high-value areas are mainly concentrated in the middle. The median-value areas are relatively great in size and connected to each other in patches in the middle and north. Meanwhile, the low-value areas are mainly concentrated in the west and south.
	Jiangpu commuting center presents a "**monocentric clustering pattern**" in terms of the degree of work—home deviation. The high-value areas are mainly concentrated in the north. The median-value areas are relatively great in size, covering almost the entire commuting center. Meanwhile, the low-value areas are scattered in the northwest.

Declaration of competing interest

This manuscript has not been published elsewhere and is not under consideration by another journal. We have approved the manuscript and agree with submission to Frontiers of Architectural Research. There are no conflicts of interest to declare.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant number 51878142).

References

Burger, M.J., Meijers, E., 2012. Form follows function? Linking morphological and functional polycentricism. Urban Stud. 49 (5), 1127—1149.

Chen, W., Liu, L., Liang, Y., 2016. Retail center recognition and spatial aggregating feature analysis of retail formats in Guangzhou based on POI data. Geogr. Res. 35 (04), 703—716.

Ding, L., Niu, X., Song, X., 2016. Measuring the employment center system in Shanghai central city:A study using mobile phone signaling data, 2016 Acta Geograph. Sin. 71 (3), 484—499.

Ding, L., Song, X., Niu, X., 2019. Characters of functional linkage of urban spatial structure: a case study of Shanghai central city. Urban Planning 43 (9), 107—116.

Ding, Ch, 2010. The impact of urban spatial structure and land use pattern on urban transportation. Urban Transport of China 8 (5), 28—35.

Guo, L., Zheng, Ch, Huang, J., 2019. Commuting circle-based spatial structure optimization of megacities: a case study of Wuhan central city. Urban Planning (10), 43—54.

Guo, X., Luo, Zh, He, H., 2016. Identification of polycentric spatial structure in megalopolis based on taxi passenger flow: a case study of Suzhou city. Urban Problem (10), 22—29.

Jiang, L., Wu, Sh, 2013. 2000-2010 Guangzhou population spatial distribution and polycentricity spatial structure evolution. Trop. Geogr. 33 (2), 147—155.

Jiang, L., Wu, Sh, 2009. A study on Guangzhou's employment subcentres and polycentricity. Urban Planning Forum (3), 75—81.

Liu, Z., Liu, S., 2018. Polycentric development and the role of urban polycentric planning in China's megacities: an examination of Beijing's metropolitan area. Sustainability 10 (5), 1—14.

Liu, Y., Fan, P., Yue, W., et al., 2018. Impacts of land finance on urban sprawl in China: the case of Chongqing. Land Use Pol. 72, 420—432.

Liu, X., Gong, L., Gong, Y., Liu, Y., 2015. Revealing travel patterns and city structure with taxi trip data. J. Transport Geogr. 43, 78—90.

Lu, Q., Kan, Ch, Wei, X., 2020. Commuting circle in twin cities of Tianjin based on location-based service data. Urban Traffic (5), 45—53.

Long, Y., Zhang, Y., Cui, Ch, 2012. Identifying commuting pattern of Beijing using bus smart card data. Acta Geograph. Sin. 67 (10), 1339—1352.

Luo, Q., Li, X., 2019. The spatial differentiation and influencing factors of urban centers in China based on VIIRS night light. Geogr. Res. 38 (1), 157—168.

Meng, Q., Chen, J., 2006. A Study on the Time-Space Characteristics of Urban Commuting. Traffic & Transportation (B07), 6—9.

Mao, Sh, Jiao, L., Xu, G., Li, Z., 2019. Identification of the polycentric spatial structure in Wuhan City based on multisource data. Prog. Geogr. 38 (11), 23—31.

Niu, X., Ding, L., Song, X., 2014. Understanding urban spatial structure of Shanghai central city based on mobile phone data. Urban Planning Forum (6), 71—77.

Shi, G., Jiang, N., Yao, L., 2017. Study on the identification of urban center system based on GIS and POI-A case study of Shanghai. Modern Surveying and Mapping 40 (6), 27—30.

Sun, B., Tu, T., Shi, W., 2013. Test on the performance of polycentric spatial structure as a measure of congestion reduction in megacities: the case study of Shanghai. Urban Planning Forum (2), 63—69.

Sun, L., Jin, J., Axhausen, K.W., Lee, D.-H., Cebrian, Manuel, 2015. Quantifying long-term evolution of intra-urban spatial interactions. J. R. Soc. Interface 102 (12), 1089.

Wei, H., Xiao, T., Hu, B., Wang, W., Wang, Ch, 2020. Analysis of residents travel behavior and urban spatial structure based on Beijing taxi GPS data. Urban Planning of Shanghai 150 (1), 77—84.

Wei, W., Zhao, G., 2005. Research on the patterns of Japanese metropolitan circles: a literature review. Contemp. Econ. Jpn. (2), 40—45.

Wu, Q., Qian, L., Wu, Zh, 2020. Research on spatial structure identification and spatial morphology of megalopolis based on multi-source data. Geomatics World 143 (5), 38—44.

Yan, Q., Li, Ch, Chen, C., 2018. Characteristics of activity space and community differentiation in Changchun: a study using mobile phone signaling data. Hum. Geogr. 33 (6), 41—49.

Yang, X., Fang, Zh, Yin, L., Li, J., Zhou, Y., Lu, Sh, 2018. Understanding the spatial structure of urban commuting using mobile phone location data: a case study of Shenzhen, China. Sustainability 10 (5), 1435.

Zhang, L., Yue, W., Liu, Y., 2017. Multidimensional analysis of the polycentric urban spatial structure: a case of Hangzhou. Econ. Geogr. 232 (6), 69—77.

Zhang, X., Xu, Y., Tu, W., Ratti, Carlo, 2018. Do different datasets tell the same story about urban mobility-A comparative study of public transit and taxi usage. J. Transport Geogr. 70, 78—90.

Zhou, M., Yue, Y., Li, Q., Wang, D., 2016. Portraying temporal dynamics of urban spatial divisions with mobile phone positioning data: a complex network approach. ISPRS Int. J. Geo-Inf. 5 (12), 240.

Zhou, C., Ye, C., 2013. Progress on studies of urban spatial structure in China. Prog. Geogr. 32 (7), 1030—1038.

Zhong, C., Arisona, S.M., Huang, X., Batty, M., Schmitt, G., 2014. Detecting the dynamics of urban structure through spatial network analysis. Int. J. Geogr. Inform. Sci. 11 (28), 2178—2199.

Zhou, S., Yan, X., 2006. Relationship between urban residential space and employment space and impact on resident trip in Guangzhou. Urban Planning (5), 13—18.