## ORIGINAL PAPER

# Exploring the influence of transportation on urban spatial structure using the spatial Durbin model: evidence from 265 prefecture-level cities in China

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## Abstract

The interactive relation between transportation and urban spatial structure remains a significant yet challenging issue in transport engineering and urban planning. Most previous studies indicate that the coordination of transportation and urban structure is conducive to solve urban diseases and promote urban sustainable development. Grounded in the theory of city-region spatial structure, this study examines the spatiotemporal dynamics of urban spatial structure from 2006 to 2019 and investigates the impact of transportation on shaping urban spatial structure in prefecture-level cities in China using spatial Durbin model. Major findings include: first, the nighttime light remote sensing data is employed to characterize urban spatial structure with the mono-centricity index ranging from 0.26 to 0.48. The coastal cities tend to exhibit the polycentric structure, while the cities in western region often display the monocentric structure. Second, there is a gradual decline in mono-centricity structure in these cities. Spatial heterogeneity in urban spatial structure is evident in eastern, central, western and northeastern China. Third, transportation significantly and positively influences spatial structure, however, the impact varies across regions and city sizes. Finally, policy implications are proposed based on these findings, such as promoting the integrated land use-transportation development, implementing targeted regional policies, and enhancing land use spatial planning.

**Keywords** Urban spatial structure, Transportation, China, Spatial Durbin model

## 1 Introduction

China has entered the stage of fast urbanization since the reform and opening policy, along with rapid economic growth, and the urbanization level has reached 63.9% in 2020, with the urban population reaching 902 million. Simultaneously, the built-up land space of various geographies and scales is rapidly expanding, with

the built-up area of cities is rapidly expanding from 9,386km$^2$ in 1985 to 60,721km$^2$ in 2020, with an average annual growth rate of 5.48% (Source: China Statistical Yearbook 2000, China Statistical Yearbook 2014). It is expected that there will be 200–300 million new urban residents in the future. The continuous increase of China's urbanization would, on the one hand, result in the continuous geographical expansion of urban space, as well as the deterioration of the ecological environment and the drastic reduction of farmland (He et al., 2020, Huang et al., 2021). On the other hand, it would complicate the city's internal spatial structure, and the excessive population concentration will increase the demand for land, transportation, employment, and housing in the urban space, further stimulating "modern urban

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diseases" such as traffic jams, overcrowding, employment difficulties, rising income polarization, and other social problems (Zhao et al., 2014, Dong and Yan, 2021). This will have an impact on the long-term and healthy development of cities and towns, as well as the process of developing a harmonious society in China.

As a crucial framework for shaping urban spatial forms, transportation facilitates the dynamic activities and distribution of elements such as human flow and logistics within cities. The enhancement of transportation networks significantly contributes to the urban and regional integration development, fostering a highly networked and collaborated regional economy (He et al., 2019). A new pattern of core-periphery relations is emerging in the Chinese economy, with notable core-peripheral disparity within many provinces, such as Jiangsu (Wei, 2002; Wei & Fan, 2000; Wei & Kim, 2002), Zhejiang (Wei & Ye, 2004; Ye & Wei, 2005), greater Beijing (Yu, 2006; Yu & Wei, 2008) and Guangdong (Gu et al., 2001; Liao & Wei, 2012; Loo, 1999; Yu, 2011). Rapid urbanization has led to transportation issues emerging as a significant impediment to the sustainable expansion of metropolitan areas. Urban transportation systems are transitioning from traditional structures based on walking and cycling to a motorized orientation. This shift has directly led to numerous social issues, including traffic congestion, environmental pollution, poor traffic safety, and unequal socioeconomic mobility (Jian et al., 2022). Consequently, resolving the conflict between the development model of transportation motorization and the conventional urban spatial structure is becoming increasingly urgent.

Transportation and urban spatial structure have a complex interaction relationship (Garcia-Lopez, 2012; Aljoufie et al., 2013b). The demand for urban transportation and the multi-mode of transportation structure are determined by urban space, whereas urban transportation modifies the accessibility of urban space, which impacts the layout of spatial form and the remodeling of spatial structure (Aljoufie et al., 2013a; Li, 2020). Furthermore, China's transportation planning has been separated from land use planning and industrial planning, resulting in a lack of coordination between transportation and urban spatial structure. It is difficult to resolve the contradiction between supply and demand for urban transportation, as well as the mismatch between urban residential and employment functions such as industrial parks and commuter towns (Wang et al., 2023). However, the existing literature on the relationship between the two is primarily based on western urban theories, which cannot be applied in China context with the socialist market economy (Xue et al., 2020). With the advent of new technologies and new methods, it is necessary to conduct theoretical and empirical analyses about their complex association between transportation and urban development.

Therefore, this paper contributes to the existing studies in the following ways. First, the night-light remote sensing images are utilized to characterize the spatial structure of a city, using the monocentric index. Second, the spatiotemporal dynamics of urban spatial structure are examined and the heterogeneous impact of transportation on formulating the monocentric structure of a city is also investigated using the spatial Durbin model. Third, the meso-scale empirical evidence from the 284 prefecture-level cities in China is conducted and policy implications are proposed to promote the coordination between transportation and land use.

Using a panel dataset of 265 prefecture-level cities in China from 2006 to 2019, this paper examines the impact of transportation on urban spatial structure, employing a spatial econometric model to analyze spatiotemporal heterogeneity. Section 2 describes literature review and section 3 explains data sources and methodology. Section 4 presents the major results and section 5 includes discussion, policy implications and limitations and prospects. Section 6 conclude major findings.

## 2 Literature review
### 2.1 The measurement and the mechanisms of urban spatial structure

The urban spatial structure refers to the arrangement and distribution of different functional areas in a city. It is the spatial manifestation of socioeconomic activities and functional organization in a specific region (Gallion, 1983; Xue et al., 2020). This structure can be categorized into monocentric and polycentric structures according to the spatial organization of population and employment within a given region. The monocentric structure emphasizes a single and highly concentrated center in the region, while the polycentric structure allows for multiple centers of concentration (Jung et al., 2022).

Measuring urban spatial structure is crucial for understanding its dynamics. Early monocentric models were primarily based on the pattern of declining density radiating from a central point. However, as the urban spatial structure become more intricate and encompasses various dimensions, the influence of monocentric models has waned, giving way to polycentric models. Methods for measuring polycentric spatial structures include parametric methods, threshold methods, and nonparametric methods. The existing literature have widely examined the metrics and assessment criteria used to analyze the spatial organization of cities. The spatial arrangement of population and socioeconomic activities as well as land use structure are fundamental to understand the dynamic

process of urban spatial structure and characterize spatial organization of various human activities (Arribas-Bel and Schmidt, 2011; Liu et al., 2022). Polycentricity encompasses both morphological and functional dimensions, with the morphological aspect focusing on the spatial distribution of population, employment, and land use (Burger and Meijers, 2012). Arribas-Bel and Schmidt (2011) measured the urban spatial structure of 359 metropolitan areas in the U.S. from the six dimensions of commuting cost, density, employment concentration, land use mixing degree, and city size. They prove the existence of significant variations in the urban spatial structure among these metropolitan areas. The built environment in the urban area is an important carrier of human social and economic activities, and is a significant aspect of urban spatial structure (Small, 2019). Liu et al. (2022) used these built environment indicators such as the area, height, and quantity of urban buildings to measure urban morphology. Yousefi and Dadashpoor (2020) categorize the urban spatial structure into four components: spatial organization, geographical characteristics, patterns of land use, and distribution of occupation and residence. Furthermore, they emphasized the importance of person-to-person interaction, diverse activities such as work, shopping, and leisure, as well as mobility, which encompasses the movement of goods, information, and individuals.

The formulation of urban spatial structure is complex and results from interactions among factors such as income, topography, transportation infrastructure, industrial structure, urban planning, and administrative policies (Yousefi and Dadashpoor, 2020). Population growth triggered by urban–rural migration is generally considered to be the main mechanism causing the dynamic changes of urban spatial structure (Dewan et al., 2012). According to neo-Marxist theory, land rent prices, real estate investment and government intervention policies are the underlying mechanisms (Miao et al. (2016). The dynamic structure of Chinese cities can be mostly attributed to the economic development, transportation, and administrative policies that have been implemented since the reform and opening up. The primary determinant of urban expansion is economic development, and transportation exerts varying impacts on urban expansion across different time periods. Administrative policy has consistently played a crucial role in the realm of Chinese urban development. Furthermore, they have a significant impact on shaping the evolution of urban spatial structure (Wu et al., 2023; Zhang et al., 2005).

## 2.2 Measurement and spatial externalities of transportation infrastructure

When assessing the transportation infrastructure of a country or region, many scholars typically rely on a singular comprehensive measure, such as transportation network density, transportation fixed investment, or commodities flow density. Démurger (2001) utilizes the traffic density method to evaluate transportation infrastructure. This involves calculating the total length of highways, railways, and inland waterways and dividing it by the land area. When considering regional integration, several scholars utilize the measure of freight turnover volume to characterize transportation infrastructure. The cargo turnover volume is calculated by multiplying the number of products delivered by different transport modes and the corresponding travel distance. This indicator can accurately reflect the production capacity in the transportation industry and can be used to make urban planning and transportation planning (Zhao and Zhang, 2018).

Because of the robust externality and spatial network characteristics of transportation infrastructure, the spatial spillover effect has garnered considerable scholarly attention. Improving the transportation infrastructure in a region can typically lower the costs of transportation and transactions within the region and between the specific region and its neighboring areas, thus stimulating economic development of those surrounding areas (Jian et al., 2022). The construction of transportation infrastructure strengthens the flow of factors, which is beneficial for balancing the spatial distribution of regional economic activities and improving the efficiency of regional economic resource utilization (Lin, 2017; Ren et al., 2022). Overall, the connectivity of transport networks largely improves the inter-city accessibility, changes the distribution of production factors and adjusts the industrial structure and population layout within the urban area (Wei et al., 2022).

## 3 The relationship between transportation and urban spatial structure

The relationship between transportation and urban spatial structure has always been an important and hot-debated issue in the field of transportation engineering and urban planning. Theoretical discussions are firstly conducted in the western countries and the representative theories include the location theory proposed by the classical economics school, the urban regional spatial structure theory proposed by the Chicago School, the theory of spatial economics, and the transportation theory proposed by the behavioral school (Zhang et al., 2018). These theoretical studies have important implications to develop effective urban planning programs and urban management policies, but it remains difficult to solve a series of social and economic problems caused by urban sprawl. From the planning perspective, Peter Calthorpe proposed the concepts such as pedestrian-friendly neighborhoods and transit-oriented land development

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models (Ibraeva et al., 2020). The integration of transportation and land use should be advocated at the regional level, with a focus on people's travel activities and transportation needs. Developed countries, such as Denmark (with its capital Copenhagen), the Netherlands, and Italy (specifically Milan), have implemented comprehensive transportation and land use management initiatives tailored to their specific regional circumstances (Zhao and Zhang, 2018). Although the integrated planning theory is mainly popular in low-density developed countries, it was subsequently promoted and applied in high-density areas, such as Singapore. However, the existing literature mainly takes the low-density urban systems in developed countries and applies the western theories, which cannot reflect the characteristics and spatial patterns of urban development in China characterized by rapid urbanization and industrialization.

Transportation infrastructure is an important factor in shaping the spatial structure of a city (Yu, 2011; Yang and Huang, 2022). The existing studies mainly focus on the impact of railway and highway construction. Salov and Semerikova (2023) analyze the influence of railway development on the formulation of employment subcenters from 1968 to 2018 in the Paris urban agglomeration. It is found that the railway networks relocate the functions as the capital to a certain extent and promote regional development in the surrounding areas along railways, which hence lead to the scattered urban structure of economic activities. Yang and Huang (2022) analyze the impact of high-speed railway stations on urban structure, employment, residential location and house rent based on the spatial balance model. It proves that the location of high-speed rail stations is important to the diversified formulation of urban structure. Gonzalez-Navarro and Turner (2018) investigate the impact of subway networks on urban population structure in global cities over the past few decades and demonstrate a significant influence of subways on the suburbanization of cities. Therefore, the distribution of transportation in urban areas would invariably influence the dispersion and agglomeration patterns of urban populations and socioeconomic activities, as well as the geographical form of cities.

With the advancement of geographic information systems, remote sensing technology, and various mathematical statistical methods, it is necessary to focus on the spatiality and the finer scale in the field of transport-land use integration by using spatial and geographic big data. The present studies employ urban population and employment to measure the urban spatial structure. However, these statistical data cannot reflect the real situation of human socioeconomic activities. The geographic big data such as the night-light remote sensing data adds a new data source, which effectively avoids the influence of endogeneity and bias in measurement data (Huang and Xu, 2021; Ye et al., 2022). Because of the widespread existence of spatial spillover effects, spatial econometric models provide a useful tool to explain the distribution of economic activities.

## 4 Data and methodology
### 4.1 Description of the study area
This study focuses on 265 prefecture-level cities in China as the case study, specifically excluding autonomous prefectures, regions, and leagues, and a limited number of cities such as Chaohu, Sansha and Danzhou, which is difficult to obtain statistical data. These 265 prefecture-level cities are categorized into four geographic regions based on their geographical location: eastern (E), central (C), western (W), and northeastern (NE). The eastern region (E) was the pioneering region in China to adopt the coastal opening policy. This region exhibits a relatively advanced level of economic development and encompasses Beijing Municipality, Tianjin city, Hebei Province, Shanghai Municipality, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central region (C) is characterized with food production and a large amount of farmland, which include the cities within Anhui, Henan, Hubei, Hunan, Jiangxi, and Shanxi Provinces. The western region (W) encompasses economically disadvantaged areas, such as Gansu, Guangxi, Guizhou, Inner Mongolia, Ningxia, Qinghai, Shaanxi, Sichuan, Tibet, Xinjiang, Yunnan, and Chongqing. Northeastern China (NE) is a region in China characterized by heavy industrial and population loss. It encompasses the cities located in Heilongjiang, Jilin, and Liaoning.

### 4.2 Data description and methods
#### 4.2.1 Data sources
The city-level statistical data is obtained from the "China City Statistical Yearbook" and "China Statistical Yearbook". The harmonized global night-time light time series data include the stepwise calibrated stable DMSP NTL observations from 1992 to 2013, i.e., F10 (1992–1994), F12 (1995–1996), F14 (1997–2003), F16 (2004–2009), and F18 (2010–2013), and the simulated DMSP-like DNs from the VIIRS radiance data (2014–2019). The spatial resolution of this dataset is 30 arc-seconds (Li and Zhou, 2017; Li et al., 2020).

#### 4.2.2 Variable description

(1) Dependent variable

The urban spatial structure (mono) can reflect the degree of urban spatial agglomeration. We utilize relative values derived from the morpho-spatial structure for

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**Table 1** Statistical description of all variables

| Variable | | Natiaonwide | | Eastern | | Central | | Western | | Northeast | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | S.D | Mean | S.D | Mean | S.D | Mean | S.D | Mean | S.D |
| *mono* | monocenter index | 0.38 | 0.18 | 0.40 | 0.20 | 0.34 | 0.15 | 0.41 | 0.18 | 0.36 | 0.19 |
| *road* | road density | 1.11 | 1.31 | 1.60 | 1.68 | 1.40 | 1.36 | 0.52 | 0.62 | 0.76 | 0.73 |
| *hfv* | highway freight volume | 9613.80 | 14557.95 | 10567.17 | 8064.03 | 10193.41 | 7672.66 | 9208.62 | 22456.02 | 7190.54 | 13524.69 |
| *ppden* | population density | 402.24 | 297.85 | 579.01 | 332.28 | 472.67 | 263.54 | 258.01 | 216.38 | 200.46 | 130.77 |
| *sat* | science and technology | 0.20 | 0.17 | 0.23 | 0.17 | 0.24 | 0.23 | 0.16 | 0.11 | 0.14 | 0.11 |
| *fassets* | fixed asset investment | 2.13 | 1.70 | 2.51 | 1.83 | 2.05 | 1.54 | 1.99 | 1.80 | 1.84 | 1.36 |
| *gov* | government intervention | 0.18 | 0.10 | 0.13 | 0.05 | 0.17 | 0.06 | 0.24 | 0.13 | 0.20 | 0.10 |
| *indus* | industrial structure | 86.20 | 8.11 | 89.50 | 5.64 | 86.90 | 7.25 | 84.06 | 8.02 | 82.55 | 11.15 |

assessment (Meijers and Burger, 2010). Using corrected nighttime light data, we extract the total brightness values of each city within administrative entire city area (including counties, county-level cities, and districts), and then use the proportion of the total values of brightness of city districts to the total brightness of the entire city area to reflect the spatial structure. The zonal statistics tool in ArcGIS is used to calculate the total grid value of the light brightness within each city.

$$\text{mono}_i = \sum_{k \in CD_i} NTLB_k \Big/ \sum_{j \in C_i} NTLB_j \qquad (1)$$

Where $\text{mono}_i$ is the spatial agglomeration degree in city $i$; a larger value of the monocenter index represents the mono-centricity of spatial structure in a city whereas a lower value indicates the polycentric structure. $\sum_{k \in CD_i} NTLB_k$ denotes the sum of nighttime light brightness value of grid $k$ within the city district of city $i$ ($CD_i$); $\sum_{j \in C_i} NTLB_j$ denotes the sum of nighttime light brightness value of grid $j$ within the entire city $i$ ($C_i$).

(2) Independent variables

The impact of transportation on the development and distribution of urban spatial structure is intricate. Regions with well-developed transportation infrastructure are more likely to attract a high-quality resources quickly, leading to the formation of urban centers. This paper measures transportation infrastructure from supply and demand perspectives. Road density, the ratio of total road mileage to the city's total area, is used as a demand-side measure. On the supply side, the capacity of transportation infrastructure is reflected by highway freight volume. These two indicators are the main

measures for evaluating a city's traffic capacity and infrastructure construction.

(3) Control variables

This paper selects population density, science and technology, fixed asset investment, industrial structure, and government intervention as control variables. The controlling variables are measured as follows: 1) population density (*ppden*) is measured by the population per unit area in each city; 2) science and technology (*sat*) is the proportion of actual science and technology expenditures to regional Gross Domestic Product (GDP); 3) fixed asset investment (*fassets*) is measured by the fixed asset investment; 4) industrial structure (*indus*) is measured by the proportion of the sum of the secondary and tertiary industry to regional GDP; 5) government intervention (*gov*) is measured by the ratio of annual local fiscal expenditure to regional GDP.

The panel data of 265 cities in China during the period 2006–2019 is constructed and Table 1 shows the statistical description of all variables across different regions.

### 4.2.3 Spatial Durbin regression
The presence of spatial autocorrelation violates the independence assumptions (Wang et al., 2022). The spatial econometric model assumes that the dependent variable is simultaneously affected by the independent variables within the specific region and the dependent variable in surrounding regions. Spatial econometric models generally include spatial autocorrelation model (SAR), spatial error model (SEM), and spatial Durbin model (SDM). Because the spatial effect exists in both dependent variable and independent variables, this study employs spatial Durbin model to investigate the impact of transportation
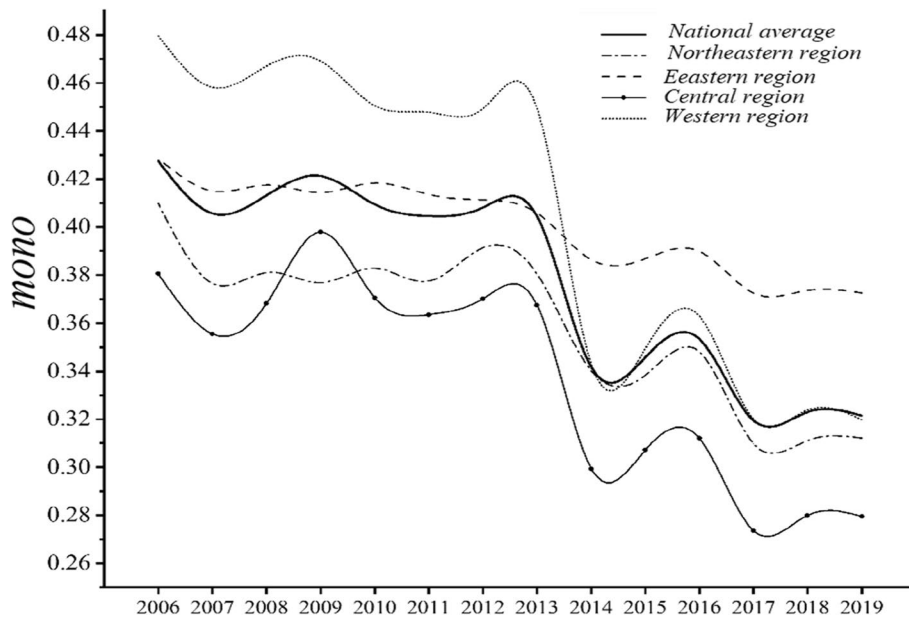
**Fig. 1** The temporal changes of the urban spatial structure in four regions of China

on urban spatial structure. The equation is listed as below:

$$mono_{it} = \rho \sum_{j=1}^{n} W_{ij} mono_{jt} + \alpha tra_{it} + \beta \sum_{j=1}^{n} W_{ij} tra_{it} + \omega X_{jt} + \tau \sum_{j=1}^{n} W_{ij} X_{jt} + \eta_i + \delta_t + \nu_{it}$$

Where $mono_{it}$ is the urban spatial structure of city $i$ in year $t$; $tra_{it}$ is transportation of city $i$ in year $t$; $W_{ij}$ is the spatial weight matrix between city $i$ and the neighboring city $j$; $\rho$ and $\tau$ are the spatial lag coefficient and spatial error coefficient; $X_{jt}$ denotes the controlling variables of city $j$ in year $t$; $\alpha$, $\beta$ and $\omega$ are regression coefficients; $\eta_i$ is the individual fixed effect; $\delta_t$ is time fixed effect; $\nu_{it}$ is the error term.

## 5 Results

### 5.1 Spatiotemporal dynamics of the urban spatial structure in prefecture-level China

Figure 1 shows the temporal dynamics of spatial structure in prefecture-level China from 2006 to 2019. We can observe that the national average value of mono-centricity index ranges from 0.26 to 0.48 during 2006–2019, and demonstrates a fluctuating downward trend with a significant decline in 2013. The dynamic changes of urban spatial structure result from the combined effects of government policy and market forces. On the one hand, the unlimited agglomeration of population into city centers has produced serious traffic congestion, environmental pollution, resource waste, which impede the high-quality

development of a city and neglect residents' demand for the high-quality living environment. Therefore, the central and local governments start to ease population and industrial pressure in the central city through constructing new industrial development zones and new towns in peripheral regions such as Xiong'an New Area, Pudong New Area and XiXian New Area. On the other hand, the market force is also pushing the outflow of population to city suburbs because of the high land price and housing price in the city center, well-developed transportation networks and beautiful ecological environment in the suburbs, hence leading to the shift of most prefecture-level cities towards a polycentric and decentralized urban spatial structure.

Furthermore, the spatial structure demonstrates obvious regional differences in China. As seen in Fig. 1, the mono-centricity index in the western region is relatively higher than other regions, whereas the eastern region observes a slow declining trend of mono-centricity index. In the under-developing western region with vast territory and dispersed population distribution, the city center plays an important role in economic trade, product and service supply and cultural exchange with foreign countries. The relatively superior natural environment, well-equipped public infrastructure and easy access to
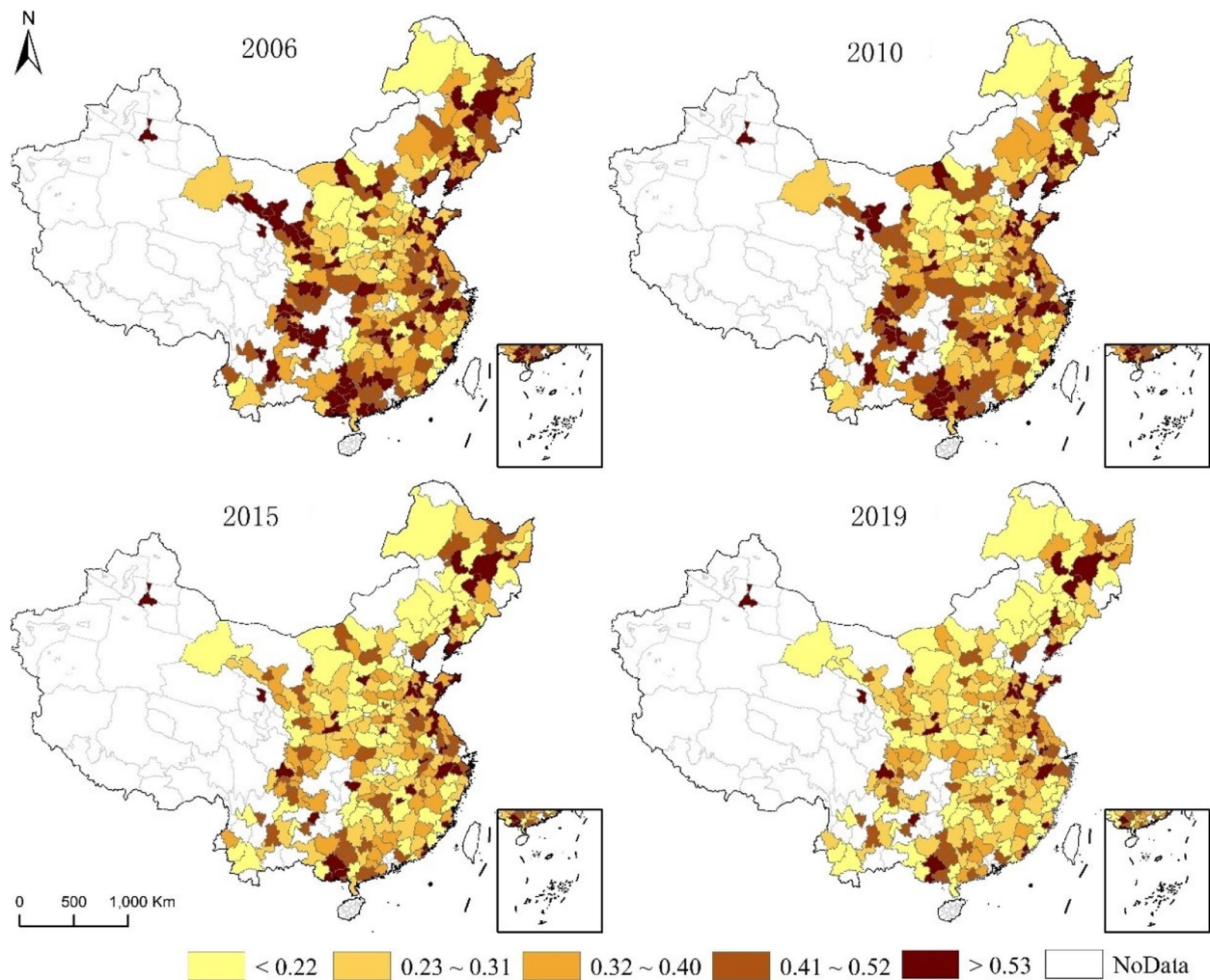
**Fig. 2** The spatiotemporal changes of the urban spatial structure in China

employment opportunities, promote a rapid concentration of labor and capital in the city center. Because of the national strategy like China's Western Development Program, the development of infrastructure, enticement of foreign investment, increased efforts on ecological protection and retention of talent flowing to richer provinces, make the city center in western region more attractive and then promote the inflow of population and urban expansion. However, regarding to the eastern, central and northeastern regions, the mono-centricity structure is declining with the trend of suburbanization driven by the polycentric urban planning policies.

Figure 2 demonstrates the spatiotemporal changes of the urban spatial structure in prefecture-level China. Overall the monocentric agglomeration in most prefecture-level cities is declining during 2006–2019. It

has been widely acknowledged for urban planners and policy-makers that polycentric urban spatial structure is essential for high-quality regional development and ease various urban diseases. The number of monocentric cities is decreasing and the polycentric spatial structure becomes the most common spatial form of urban agglomerations. The monocentric cities with a high value of mono-centricity index above 0.53 are mainly distributed in the western region (e.g., Xi'an, Urumqi, Tongchuan), in the northeastern region (e.g., Daqing, Qitaihe) and in the eastern region (e.g., Shantou, Jinan, Zhoushan, Changzhou, Hangzhou). However, the cities with a low value of monocentric index tend to show spatial clustering. Therein, these prefecture-level cities such as Shantou, Jinan, Urumqi, Xi'an, Zhoushan, have the highest mono-centricity index above 0.80, as seen in Table 2.

**Table 2** The top ten prefecture-level cities according to the value of mono-centricity index

| 2019 | | | 2015 | | | 2010 | | | 2006 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rank** | **City name** | **Value** | **Rank** | **City name** | **Value** | **Rank** | **City name** | **Value** | **Rank** | **City name** | **Value** |
| 1 | Shantou | 0.977 | 1 | Shantou | 0.981 | 1 | Shantou | 0.990 | 1 | Shantou | 0.991 |
| 2 | Jinan | 0.888 | 2 | Jinan | 0.889 | 2 | Urumqi | 0.904 | 2 | Urumqi | 0.933 |
| 3 | Xi'an | 0.816 | 3 | Xi'an | 0.836 | 3 | Jinan | 0.898 | 3 | Tongchuan | 0.931 |
| 4 | Zhoushan | 0.813 | 4 | Changzhou | 0.828 | 4 | Tongchuan | 0.897 | 4 | Jinan | 0.902 |
| 5 | Changzhou | 0.797 | 5 | Zhoushan | 0.824 | 5 | Hangzhou | 0.851 | 5 | Xi'an | 0.893 |
| 6 | Urumqi | 0.771 | 6 | Urumqi | 0.808 | 6 | Xi'an | 0.844 | 6 | Hangzhou | 0.875 |
| 7 | Hangzhou | 0.753 | 7 | Hangzhou | 0.789 | 7 | Changzhou | 0.825 | 7 | Zhoushan | 0.826 |
| 8 | Daqing | 0.731 | 8 | Tongchuan | 0.783 | 8 | Zhoushan | 0.817 | 8 | Changzhou | 0.825 |
| 9 | Tongchuan | 0.729 | 9 | Qitaihe | 0.767 | 9 | Xinyu | 0.810 | 9 | Xinyu | 0.824 |
| 10 | Qitaihe | 0.699 | 10 | Xinyu | 0.752 | 10 | Putian | 0.754 | 10 | Tongling | 0.785 |

**Table 3** Results of LR and Wald tests for spatial econometric model

| Test Indicator | Test Method | Statistic | *P*-value |
|---|---|---|---|
| LM test | LM test no spatial lag | 607.590 | 0.0000 |
| | LM test no spatial error | 1033.559 | 0.0000 |
| Robust LM test | Robust LM test no spatial lag | 30.308 | 0.0000 |
| | Robust LM test no spatial error | 456.277 | 0.0000 |
| LR test | LR test spatial lag | 240.29 | 0.0000 |
| | LR test spatial error | 233.65 | 0.0000 |
| Wald test | Wald test spatial lag | 74.30 | 0.0000 |
| | Wald test spatial error | 54.21 | 0.0000 |

**Table 4** Estimation results of the impact of transportation on the urban spatial structure

| Variables | Spatial Durbin model | | |
|---|---|---|---|
| | **Direct effect** | **Indirect effect** | **Total effect** |
| *lnroad* | -0.007** | -1.748*** | -1.756*** |
| | (-2.35) | (-2.66) | (-2.66) |
| *lnhfv* | -0.008*** | -0.643* | -0.651* |
| | (-3.75) | (-1.70) | (-1.71) |
| *ppden* | 0.000*** | 0.068*** | 0.069*** |
| | (3.96) | (3.04) | (3.05) |
| *sat* | 0.015** | 1.895** | 1.910** |
| | (2.06) | (2.06) | (2.07) |
| *fassets* | 0.002 | 0.340** | 0.341** |
| | (1.50) | (2.20) | (2.20) |
| *gov* | -0.050** | 0.348 | 0.299 |
| | (-2.32) | (0.17) | (0.15) |
| *indus* | -0.002*** | -0.324*** | -0.326*** |
| | (-3.56) | (-3.02) | (-3.03) |
| $\rho$ | 0.960*** | | |
| $N$ | 3710 | | |
| $R^2$ | 0.077 | | |

* 10% significance level, ** 5% significance level, *** 1% significance level

## 5.2 Exploring the influence of transportation on the urban spatial structure

This study employs spatial econometric model to examine the impact of transportation on the urban spatial structure in prefecture-level China. Table 3 presents the results of LR and Wald tests and the outcomes demonstrate that spatial Durbin model is more appropriate than spatial autoregressive model and spatial error model. The estimated results derived from the spatial Durbin model are detailed in Table 4.

Table 4 presents the results of a Spatial Durbin model, analyzing the influence of various factors on urban spatial structure. Both road density (*lnroad*) and highway freight volume (*lnhfv*) show statistically significant negative impacts on urban spatial structure. This indicates that a well-developed transportation infrastructure stimulates the evolution towards a polycentric city structure. Improved transportation reduces communication costs, enhances knowledge spillovers, and expands the geographic space for human interactions. It facilitates population dispersion towards city peripheries, shaping a polycentric spatial structure. Additionally,

transportation's spatial effects extend to neighboring cities, promoting industrial relocation and reshaping travel demands, thus reinforcing polycentric structures in prefecture-level cities in China.

The model reveals a positive and statistically significant impact of population density on urban spatial structure at the 10% level. This suggests that higher population densities in prefecture-level cities tend to favor a monocentric spatial structure. Science and technology have a positive and significant impact on the monocentric structure at the 5% level. Geographic concentration of

**Table 5** Results of heterogeneity analysis of region

| Variables | Eastern Total effect | Central Total effect | Western Total effect | Northeast Total effect |
|---|---|---|---|---|
| *lnroad* | 0.272*** | 0.064 | -0.613*** | -0.483*** |
| | (2.87) | (0.28) | (-4.11) | (-3.01) |
| *lnhfv* | -0.231** | -0.011 | 0.145 | -0.141** |
| | (-2.57) | (-0.09) | (1.63) | (-2.25) |
| *ppden* | 0.005** | 0.004* | -0.002 | 0.013** |
| | (2.35) | (1.67) | (-0.56) | (2.05) |
| *sat* | -0.065 | -0.779* | 0.585* | -0.351 |
| | (-0.29) | (-1.94) | (1.66) | (-1.01) |
| *fassets* | 0.095*** | 0.029 | 0.020 | 0.118*** |
| | (2.88) | (0.44) | (0.40) | (3.47) |
| *gov* | -2.766** | 0.631 | -1.254* | 0.560 |
| | (-2.25) | (0.35) | (-1.92) | (1.48) |
| *indus* | -0.043** | -0.017 | 0.025* | -0.030*** |
| | (-2.09) | (-0.71) | (1.73) | (-2.93) |
| $\rho$ | 0.870*** | 0.890*** | 0.796*** | 0.699*** |
| | (27.68) | (33.58) | (19.64) | (10.82) |
| N | 1022 | 1092 | 1120 | 476 |
| $R^2$ | 0.278 | 0.509 | 0.621 | 0.295 |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

research institutions enhances downtown core functions and attracts advanced scientific and technological activities. Additionally, advancements in science and technology contribute to industrial upgrading, especially in high-tech and electronic information manufacturing industries. The positive and significant influence of fixed asset investment on the formation of a monocentric structure at the 5% level indicates that increased investment in fixed assets is linked to intensive urban development, business clustering, and real estate concentration. The findings suggest that government intervention leans towards forming a balanced regional development pattern. It supports cities with greater potential and better resource endowments, leading to a polycentric spatial structure in urban agglomerations. The negative impact of industrial structure on the spatial structure of the city is significant. The upgrading of the industrial structure improves resource allocation efficiency, forming economies of scale and promoting the development of a multi-center structure within the region.

## 5.3 Heterogeneous influence of transportation on the urban spatial structure

### 5.3.1 Heterogeneity analysis of geographical regions

To explore geographical heterogeneity, this study divides the cities under consideration into four regions: eastern, central, western, and northeastern. The results presented in Table 5 reveal significant regional differences in

how transportation infrastructure impacts urban spatial structure. In the eastern region, the positive and significant coefficient for road density (*lnroad*) indicates that transportation infrastructure development is associated with increased population agglomeration and a tendency towards a monocentric urban structure. This could be due to that enhanced transportation infrastructure might encourage further concentration of economic activities in already developed cities in the eastern region. Conversely, in the western and northeastern regions, road density has a significant negative effect. This suggests that improvements in transportation infrastructure in these less economically developed areas encourage the dispersion of population and economic activities. As a result, urban spatial structures in these regions are evolving towards a more polycentric and flattened pattern. This trend could be driven by high housing and land prices in certain areas, prompting residents and businesses to relocate to more affordable locations, facilitated by the improved transportation network. The central region presents a unique scenario where the coefficient for road density (*lnroad*) is not statistically significant, indicating a different or less pronounced impact of transportation infrastructure on urban spatial structure compared to other regions.

Additional variables, such as highway freight volume (*lnhfv*), population density (*ppden*), satellite city development (*sat*), fixed asset investment (*fassets*), and government intervention (*gov*), show varied effects across regions. Notably, fixed asset investment (*fassets*) has a significant positive impact in the Eastern and Northeastern regions, highlighting regional disparities in how economic factors influence urban development. These findings underscore the importance of considering regional characteristics when analyzing the effects of transportation infrastructure on urban spatial structures.

### 5.3.2 Heterogeneity analysis of city sizes

This study categorizes cities into three sizes[1]—large, medium, and small—based on their population to analyze variations among them. Table 6 illustrates the results of this heterogeneity analysis. For large cities, the effects of road density (*lnroad*) and highway freight volume (*lnhfv*) on the monocenter index are significantly negative, indicating that both road density and highway freight volume are inversely related to the concentration of urban activities in a single center. In contrast, these relationships are not statistically significant in medium-sized

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[1] Cities with a population of less than 500,000 are classified as small cities, those with a population between 500,000 and 1 million are classified as medium-sized cities, and those with a population of over 1 million are classified as large cities.

**Table 6** Results of heterogeneity analysis of city sizes

| Variables | Large cities | Medium cities | Small cities |
|---|---|---|---|
|  | Total effect | Total effect | Total effect |
| *lnroad* | -0.753[*] | -0.113 | -0.089 |
|  | (-1.86) | (-0.55) | (-1.36) |
| *lnhfv* | -0.815[**] | 0.124 | -0.164[***] |
|  | (-1.99) | (1.52) | (-2.83) |
| *ppden* | 0.043[***] | 0.002 | 0.011[***] |
|  | (2.93) | (0.64) | (2.98) |
| *sat* | 0.449 | 0.505 | 0.105 |
|  | (0.70) | (1.33) | (0.68) |
| *fassets* | 0.110 | 0.062 | 0.015 |
|  | (1.10) | (1.13) | (0.86) |
| *gov* | -2.538 | -0.426 | 0.477[**] |
|  | (-0.70) | (-0.57) | (2.19) |
| *indus* | -0.124[**] | -0.100[***] | -0.017[**] |
|  | (-2.33) | (-3.07) | (-2.11) |
| $\rho$ | 0.946[***] | 0.847[***] | 0.555[***] |
|  | (68.03) | (24.23) | (7.57) |
| N | 2058 | 1204 | 448 |
| $R^2$ | 0.163 | 0.260 | 0.499 |

[*] $p < 0.1$, [**] $p < 0.05$, [***] $p < 0.01$

cities. In small cities, while the coefficient for road density remains non-significant, the coefficient for highway freight volume (*lnhfv*) is significantly negative at the 99% confidence level. This suggests that an increase in highway freight volume is associated with a more dispersed urban structure in smaller cities.

The data also reveal differences in the impact of other variables across city sizes. Population density (*ppden*) shows a significant positive effect in large and small cities, but not in medium-sized cities. Conversely, the industrial structure (*indus*) exhibits a significant negative impact in large and small cities, and an even stronger negative effect in medium-sized cities. These results suggest that larger cities with larger populations and more extensive spatial development needs are more sensitive to changes in transportation infrastructure. This infrastructure plays a pivotal role in shaping their internal spatial structure. Strengthening transportation networks enhances connectivity among cities of different sizes, facilitating economic activities in areas with lower housing and land costs. This, in turn, may encourage a shift towards a more polycentric urban spatial structure.

# 6 Discussion and policy implications
## 6.1 Discussion
This study demonstrates the significant impact of transportation on urban spatial structure in prefecture-level cities in China. It reveals both corridor and agglomeration

effects of transportation, aligning with the findings of Fan et al. (2009), which suggest that well-developed transportation tends to foster a monocentric urban structure. On one hand, an efficient public transport system compresses space–time, reducing travel time and costs, and enhancing city accessibility. On the other hand, a robust transport system facilitates the free flow of talent, capital, information, and innovation, leading to their clustering in larger cities, as noted by Démurger (2001). However, in the long term, this trend does not necessarily imply that large cities exert a "siphon effect" on smaller surrounding cities. As large cities develop, they face congestion effects and undergo transformations in industrial structure and enhancement of enterprise innovation capabilities. Improved transportation infrastructure benefits cost-sensitive industrial enterprises, encouraging them to shift their focus to smaller and medium-sized cities for better returns and expanded reproduction. Consequently, these cities can optimize resource allocation through their complementary advantages.

A well-developed transportation system also influences the spatial form of cities. From an enterprise perspective, a compact urban form aids in centralizing industrial enterprises and improving the energy efficiency of industrial production (Li et al., 2021). However, industrial agglomeration beyond a certain threshold can lead to congestion, negative externalities, increased air pollution, and reduced energy efficiency. The concentration of enterprises in city centers significantly increases commuting distances, exacerbating spatial imbalances between workplaces and residential areas (Wang & Chai, 2009). Therefore, in large cities, a shift from a monocentric to a polycentric structure is vital to alleviate overcrowding, guide the rational distribution of population and infrastructure, and enhance environmental quality.

## 6.2 Policy implications
The integrated development of transportation and land use can effectively enhance factor mobility and optimize urban structure. Firstly, urban spatial structure optimization should be tailored to local conditions, leveraging the comparative advantages of different urban areas. In the eastern region, a development pattern focusing on a modern service economy in central cities and a production-based economy in secondary cities is advisable. Strengthening economic linkages and labor division among cities and facilitating the integrated development of multiple urban centers are crucial. Additionally, for larger cities, optimizing the polycentric spatial structure, enhancing inter-city labor division and connections, and coordinating the development of large, medium, and small cities is necessary. Second, it is essential to strengthen the division of labor and connections between

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central and smaller, medium-sized cities. This approach addresses the pressure on central cities, improves connectivity between smaller cities and central hubs, and fosters a multi-center networked spatial structure. Lastly, spatial planning plays a pivotal role in achieving high-quality urban development and sustainability. Integrating spatial planning with transportation planning can optimize the spatial layout of industrial enterprises, enhance energy efficiency, and curtail urban sprawl.

### 6.3 Limitations and prospects

This study aims to examine the association between transportation and spatial structure by taking the case study of 265 prefecture-level cities in China. However, this paper has several limitations which can be resolved in the future. First, transportation can be measured from travel demand and transportation supply and the geographic big data such as taxi trajectories, public bus cards and subway cards, can be used to investigate the formulation of spatial structure. We only derive the statistical data from statistical yearbooks, which cannot uncover how people use transportation infrastructure. Second, the association between transportation and spatial structure may be nonlinear. It would be interesting to use some machine learning models to uncover their nonlinearity. Therefore, in the future studies we can focus on the finer-scale counties in China to study their association between transportation and spatial structure, which can help to enhance county economy and revive rural development. The fusion of geographic big data, spatial analysis and machine learning models can be conducted to investigate the nonlinear and spatial effects of transportation on the formulation of spatial structure.

### 7 Conclusions

This study takes 284 prefecture-level cities in China as the case study and utilizes spatial Durbin model to examine the impact of transportation on the formulation of spatial structure from 2006 to 2019. The nighttime light remote sensing data and geospatial analysis are employed to characterize the spatiotemporal patterns of spatial structure in prefecture-level China. The following major findings can be obtained. First, the nighttime light remote sensing data is used to characterize the spatial structure of cities and the mono-centricity index is constructed to measure spatial agglomeration and spatial layout. The decline of mono-centricity index can be observed in prefecture-level China especially in 2013. The spatial structure of cities in China demonstrates regional differences. Therein, the western region has relatively high mono-centricity index but a low value in eastern region. Second, transportation has a significant and positive

impact on the formulation of a polycentric structure in prefecture-level China. However, the influence of transportation infrastructure on spatial structure varies based on geographical region and city size. Besides transportation, population density, fixed asset investment, industrial structure, science and technology, and government intervention have significant impacts on spatial structure. Finally, we propose some policy options to optimize the spatial structure of cities in China such as promoting the integrated transportation development, making targeted regional policies and enhancing polycentric spatial planning.

**Availability of data and materials**
The data and materials in this manuscript are available upon request.

## Declarations

**Competing interests**
All authors declare no competing interests.

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