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How Does Polycentric Urban Form Affect Urban Commuting? Quantitative Measurement Using Geographical Big Data of 100 Cities in China

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Abstract: The relationship between polycentric urban form and urban commuting has been widely debated in Western academic circles. However, qualitative and quantitative studies have not reached a unified conclusion. The evolution of urban form in China is remarkably different from that of developed Western countries. Many Chinese cities have begun using polycentric structures as their future development strategies. This study quantitatively measures whether polycentric urban form can improve commuting efficiency in China by using traditional statistics and emerging geographic big data. We use the polycentric index (PI) as the dependent variable and the congestion delay index (CDI) and mean traffic speed (MTS) as the main independent variables. Control variables include urban morphological space compactness (CT), number of private cars per thousand people (PC), number of buses per thousand (PB), urban road area per capita (PUA) and urban population density (PD). Regression models are employed to detect the relationships among the variables. The main research conclusions are as follows: (1) A high degree of PI results in low CDI and fast MTS; (2) a compact spatial form increases the impact of polycentricity on commuting efficiency; (3) maturity road infrastructure is an important measure to promote urban commuting under a polycentric urban form; and (4) the order of effect magnitude of polycentricity on MTS is PD > PC > CT > PUA > PB; on CDI, PD > PC > PB > CT > PUA. The results can be used in examining whether the current polycentric urban pattern planning in China's cities can effectively improve commuting efficiency. They also provide a reference for the healthy development of China's urban space and policy formulation of subsequent urban planning.

Keywords: polycentric; urban form; commuting; big data; China

1. Introduction

Urban spatial structure is the result of various natural, social and economic factors in a city. Its rationality affects the production, life, environment and traffic of the city [1–5]. Polycentric urban form is generally considered as an ideal urban spatial structure which can produce great agglomeration externalities and promote social, economic, and environmental goals [6,7]. Polycentric urban form has attracted considerable attention among urban researchers [8–13].

1.1. Literature Review and Research Gap

Polycentric structure affects the spatial distribution of urban population, industry, and infrastructure. It forms a complex spatial layout and interaction model among these elements, which are linked by traffic. The spatial structure of a city has a considerable effect on the development of urban transportation, from the spatial distribution of sources to the choice of transportation modes. However, identifying which kind of traffic-efficient urban spatial structure can shorten commuting time and distance has sparked heated debates among Western academic circles. The main debate has focused on whether to support monocentric or polycentricity urban structures [14,15]. Monocentricity proponents believed that polycentricity has not reduced urban transport demand. Instead, it has increased traffic commuting distances among urban residents in Southern California [16], Los Angeles [17], San Francisco Bay Area [18], Greater Oslo [19], Seoul [20], and French Metropolitan Areas (Paris, Lyon, and Marseille) [21], among other regions. Such findings are verified from the levels of employment centers and individual commuter. The average commuting time between two regions which have different spatial structure characteristics during the same period [22–24] or have spatial structure changes in the same region at different times [25–27] are compared. Polycentricity supporters found that polycentricity has the potential to shorten commuting time. They even constructed a co-location hypothesis to explain it. They claimed that companies and residents avoid traffic jams and high land prices by constantly adjusting their residential locations to achieve balance between accommodation and employment, thereby reducing commuting distance and time [25,28]. With this ongoing debate, new supporting or opposing empirical case areas continue to emerge. However, most of these empirical tests come from Western European and American countries. Empirical research in China is lacking, considering that it is a populous, rapidly urbanizing country with a high demand for cars [15].

The spatial pattern of urban space in China is different from the multinucleated, decentralized compact development of Western megalopolis or polycentric metropolis which indicates a chain of roughly adjacent metropolitan areas (or cities) within a large region become interconnected in population and economic activities [29]. China's feature has remarkable 'introverted' features, with a divided and relatively closed function. Major reforms on China's unit and housing systems in the market economy environment occurred in the 1980s. Since then, the era of the work units providing welfare housing under a planned economic system has come to an end. Urban residents have to rent or purchase commercial houses through marketization. Such a scenario has led to the disintegration of residential structures that highly mixed with various functions, such as workplace, residences, and service facilities; moreover, the functions of the industrial, residential and living facilities have been separated [30,31]. This division of urban spatial form is accompanied by the rapid growth of urban private cars, causing serious traffic congestion and environmental pollution. The annual losses due to traffic congestion are substantial, especially in large cities like Beijing and Shanghai. The National Institute for Development of Peking University calculated the cost of Beijing traffic according to the city's average hourly wage, congestion delay and number of commutes in 2014, and the results showed that Beijing's congestion costs approximately 70 billion yuan each year [32]. The concentration of urban employment resources in an urban center is one important cause of these problems. Beijing remains a monocentric structure with a few emerging subcenters of jobs [33]. Job-accommodation separation covers a wide range of income groups. Numerous working-class families live in suburban areas while most of them work in the city center, so they spend much time in daily commuting [34]. Apart from Beijing, other big cities in China face similar congestion problems.

A strategy must be formulated to effectively alleviate the urban disease caused by excessive concentration of urban resources (e.g., traffic jams and urban sprawl). As a major strategy for future urban planning, the development of polycentric urban patterns has been sought after by many Chinese scholars and government policymakers [35–37]. According to a survey conducted by the National Development and Reform Commission of China on 144 cities, 133 cities plan to establish new cities and towns around the existing cities [7]. Both the local and national governments have introduced the 13th five-year plan, which regards the 'new form of urbanization' plan as the cornerstone of future development of urban and rural areas [5,7]. The dispute between monocentricity and polycentricity has lasted for more than 20 years. China's urban planning decision makers have chosen to support polycentric urban structure. However, can the polycentric urban structure really improve the commuting efficiency in China if short commuting time and distance are used as the main metrics? This problem has attracted considerable interest from scholars, whose research and arguments focus on individual cities, such as Beijing [15,33,38], Shanghai [39,40], Shenzhen [41], and Xi'an. Large, encompassing samples are quite scarce. The only sporadic studies, such as Song et al. [42] analyzed the impact of urban morphology represented by compactness, spatial agglomeration, scale, and density on commuting based on 35 Chinese cities. However, such studies do not involve polycentric urban structure. In addition, the selected samples are all large cities and megacities in China, and they cannot accurately reflect the actual characteristics of China's diverse cities. Sun et al. [43] used 164 cities as samples, providing a more comprehensive coverage. They analyzed the influence of urban spatial forms including the polycentricity index on commute duration. The results show that commute duration and polycentricity is negatively related, indicating that the polycentric distribution of urban employment can reduce the commuting time in Chinese cities. However, most of the previously used data are based on traditional methods, such as sociodemographic statistics and social survey data. Such traditional methods are limited by administrative boundaries or the number of survey samples. Therefore, their conclusions may be biased compared with sophisticated emerging big data methods, such as geographic big data measurements. To fill the gap, the present study uses the Landscan population spatial data with a resolution of 1 km grid. The commuting data of China's 100 most traffic-congested cities were collected from a navigation map provider based on GPS trajectory big data. This study aims to determine whether the polycentric spatial structure can improve commuting efficiency in the new data environment.

1.2. Reseach Questions, Aims and Innavotion

The urbanization rate of China is still far behind that of developed Western countries. Many things can still be improved, and huge opportunities are available for shaping China's future urban form [44–46]. This study intends to explore whether the current polycentric urban pattern planning in Chinese cities can effectively improve commuting efficiency. It also aims to provide a reference for the healthy development of urban space in China and the formulation of subsequent urban planning policies. This paper attempts to re-measure the traditional question in the new data environment, breaking the limitation of administrative boundaries, and providing a more granular and human-scale understanding of how urban spatial structures influence commuting efficiency. This paper is a preliminary exploration to the urban structure design in the Chinese context.

2. Materials and Methods

2.1. Variable Selection and Data Calculation

2.1.1. Commuting Variables

The ordinary least squares (OLS) regression of the least squares principle is used to verify whether 'polycentric spatial structure can improve commuting efficiency'. The dependent variable is commuting efficiency, and the independent variable is urban polycentricity index. Commuting efficiency is usually expressed in commuting distances (CDs) and commute times (CTs) in past studies. Traditional approaches, such as census tracts and questionnaire surveys, often capture CD and CT [15,18–20,47,48]. The rapid development of information and communication technologies (ICTs) in the last decade lead urban analysts and theorists to use such technologies to re-evaluate the urban evolution, structure and spatial behavior of cities [49]. The gradual maturity of mobile information equipment (GPS, smart phones and IC cards) has provided a new measure for urban commuting.

The 100 cities selected as the study area are from 'The Report on the Traffic Analysis of Major Cities in China for the Second Quarter of 2017'. This report was published by author institutions, such as Gaode Map and the Institute of National Transport Ministry. The Gaode Map is a leading provider of navigation and location-service solutions in China. Their report is based on the massive traffic data of 700 million users. They identified the top 100 traffic-congested cities through big data mining algorithms, and the top 100 cities were selected as the study area of this research (Figure 1).

Figure 1. Study cities and their locations.

The degree of city commuting congestion was evaluated using the congestion delay index (CDI) (measured as Equation (1)) and mean traffic speed (MTS). These two indices express the time cost caused by traffic and the extent of traffic flow within the city in a comprehensive manner from the perspective of travellers. CD and CT are often applied to the study of commuting in a single or a small number of cities. Thus, the influence of city size can be ignored. A large research sample results in greater uncertainty in terms of the scale of city because the indicators may or may not be obtained under similar conditions. However, the indicators of CDI and MTS can ensure that all samples are based on the same standard for eliminating the uncertainty brought about by CD and CT. They can replace CD and CT as indicators of commuting efficiency. Figure 2 shows the CDI and MTS of the 100 cities.

$$\mathrm{CDI} = \frac{\mathrm{TT}}{\mathrm{FFT}} \quad (1)$$

where TT means the total travel time and FFT is free-flowing traffic time.

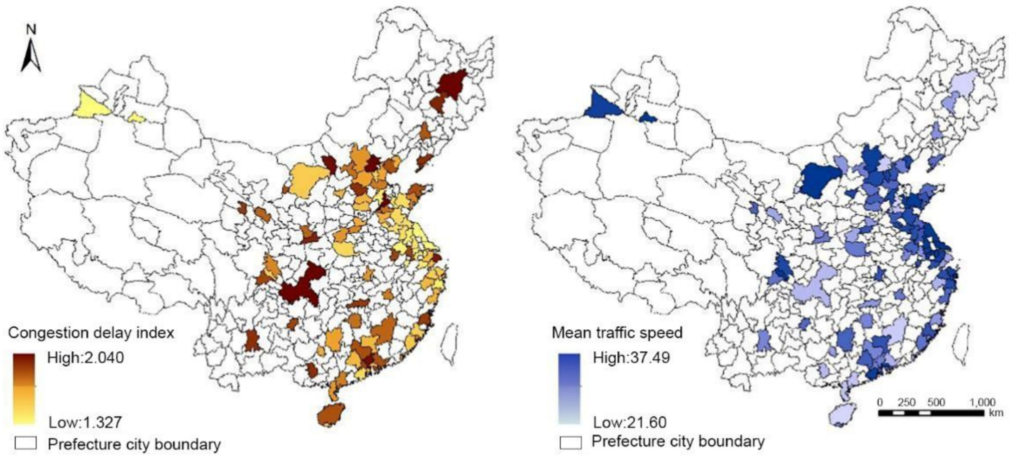

Figure 2. CDI and MTS of the 100 cities.

2.1.2. Polycentric Variables

In this study, urban polycentric structure is measured using Landscan data released in 2015. Currently, Landscan has the highest accuracy in population spatial distribution data. It has a spatial resolution of 1 km, developed by the US Department of Energy's Oak Ridge National Laboratory. It breaks through traditional demographic statistics based on administrative regions [7]. Moreover, it uses spatial data, image analysis techniques and multivariate dasymetric modelling methods in which census-aggregated units are disaggregated into raster-based data of higher spatial resolution, to decompose the census data within the administrative boundary, directly demonstrating the spatial distribution of the population [50].

Traditional polycentricity usually refers to urban employment centers, rather than the population distribution center expressed by Landscan. A spatial mismatch exists between the two (job-housing imbalance). However, in China, the population center is still considered when relevant policies are established [7,51]. Urban development issues in terms of urban form, land use layout, configuration of infrastructures, public services, transportation system, and housing could be addressed within the urban Master plan. The provisions of public services and infrastructure are often based on redistribution/control of population [48]. Using the population center as a polycentric measure of the city still has a strong practical significance in China. For example, Liu et al. have used the Landscan dataset to measure the polycentricity, and presented rational explanation of using population centers rather than traditional employment/activity/service centers for Chinese cities [7,52]. In reference to Sun's research [43], the polycentricity index for each city is calculated according to Equation (2). Such calculation considers not only the rank-size distribution of different population centers but also the spatial proximity among them. A higher polycentricity index indicates a more evenly population spatial distribution of the city:

$$\text{polycentricity} = \sqrt{\frac{\sum_{i=1}^{n} (\ln(d_i + 1) * x_i)^2}{n}} \tag{2}$$

where d_i represents the ratio of the distance between the *i*th population's subcenter and the main center to the subcenter farthest from the main center. x_i indicates the population ratio of the main center of the population of the *i*th population subcenter.

However, Sun et al. [43] used the population density of administrative area (e.g., districts or counties) to calculate the population index. This strategy calculates the population center without breaking administrative boundaries. Landscan provides refined spatial resolution (1 km) population distribution which allows an accurate identification of population distribution centers. Population center is represented as a highly populated area with spatial clusters. Thus, Getis-Ord Gi* [53,54] can be used to identify statistically significant hot spots as population centers. Getis-Ord Gi* uses Z-scores to determine spatially high or low clustering status of variables. Statistically positive and large Z-scores indicate that high-value (hot spot) clustering is strong, whereas a low Z-score means that the low-value (cold spot) clustering of the values is strong. The statistically significant level at 0.05 or 0.01 corresponds to a cutoff of ± 1.96 or ± 2.58. Getis-Ord Gi* is available in commercial GIS software packages, such as ESRI's ArcGIS. Using ArcGIS 10.2 software (ArcGIS 10.2, California, LA, USA; Wuhan University, Environmental Systems Research Institute, Inc.), the computational procedure of urban polycentricity index is as follows:

(1) Convert the raster form of Landscan to vector form to identify the spatial distribution of population.
(2) Extract hot spot plots, and identify populations covered by map spots in each hot spot region by superimposing data with population spatial distribution.
(3) Extract the four hot spot plots with the largest population, and calculate the urban polycentricity index according to Equation (2).

2.1.3. Control Variables

In addition to the polycentricity index as the explanatory variable, the urban morphological space compactness (CT), number of private cars per thousand people (PC), number of buses per thousand (PB), urban road area per capita (PUA), and urban population density (PD) are used as control variables on the principle of data acquisition. High compactness of urban space can improve the mixed degree of land use, and land use mix can considerably affect the travel needs of urban residents [55,56]. PUA is an important indicator of the urban development level in China, reflecting the level of urban traffic accessibility to a certain extent. In general, a higher PUA value indicates more road length and better traffic capacity of a city. PB and PC reflect the urban residents' choice of private and public travel behavior. PD is measured by the number of persons per square kilometer within urban built-up areas. Generally, low-density development is recognized as one of the basic components of urban sprawl and associated with long vehicle miles traveled, which in turn results in a low urban commuting efficiency [57,58]. The data of PUA, PB, PC, and PD are obtained from the 2015 Chinese Urban Statistical Yearbook. The data on CT are derived from calculation result of construction land use from the 2015 National Land-Use/Cover Database of China (NLUD-C) produced by the Chinese Academy of Sciences [59]. The calculation formula is as follows:

$$\mathrm{CT} = \frac{2\sqrt{\pi \mathrm{A}}}{\mathrm{L}} \tag{3}$$

where A represents the area of built-up, L represents the circumference of the build-up, and π (3.14) represents the circumference rate.

2.2. Regression Analysis

The multiple linear regression analysis has been widely used in previous studies on the effect of urban morphology on commuter behavior [15,43,47]. Several multiple linear regression models were created to reveal the effect of urban polycentric structure on the commuting. They are used to investigate the relationships among CDI, MTS and six independent variables (one polycentric index and five control variables). Moreover, each of the control variables are involved in the linear regression modelling.

3. Result and Discussion

3.1. Polycentric Index of Study Cities

Using the LandScan population spatial distribution data, the population cluster center of each city was identified via Getis-Ord Gi*. Sanya is the only city with only one population center, whereas Shanghai has the largest number of centers totaling 12. The most populous center is located in Beijing, with a total of more than 2 million people. On average, each city has 3.8 population centers, and the size of population of each center is 2.705×10^5. With the spatial location of the population center and the population number of each center identified as basis, the distance between each center is obtained using the GIS software, and the polycentric index (Figure 3) of each city is obtained through Equation (2).

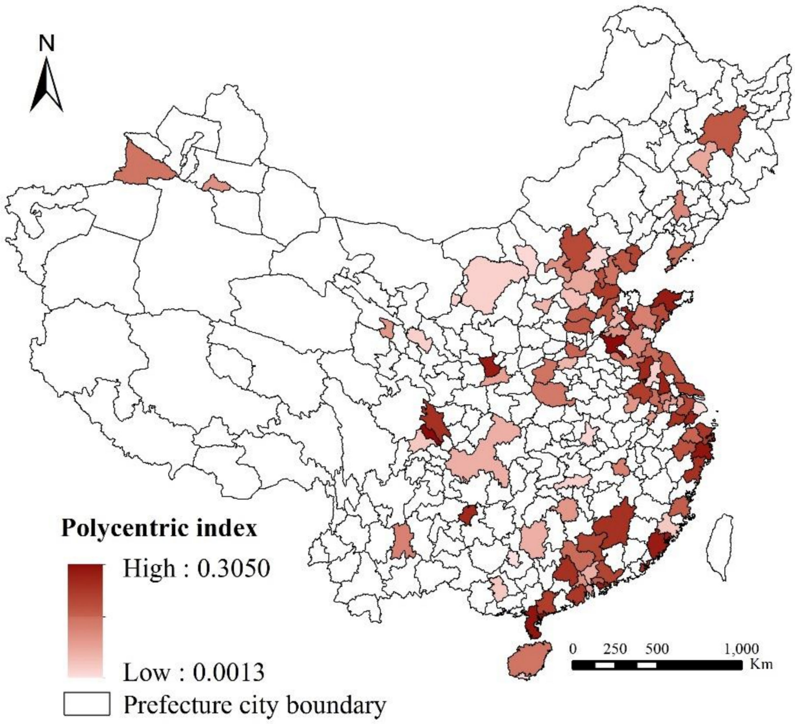

Figure 3. Polycentric index of each city.

3.2. Regression Results and Analysis

The variance inflation factor (VIF) of all independent variables was detected before the regression models. The VIF values for polycentricity, CT, PC, PB, PUA, and PD were 1.073, 1.228, 2.065, 1.987, and 1.632, respectively. Values that are less than 4 indicate that the multiple collinearity between variables does not affect the analysis of the results [4]. The statistics of variables in the regression equation are shown in Table 1.

Table 1. Statistics of dependent and independent variables.

Variable	Unit	Minimize	Maximize	Mean	Standard Deviation
CDI	N/A	1.327	2.040	1.674	0.138
MTS	km/h	21.600	37.490	26.961	3.384
Polycentricity	N/A	0.001300	0.305000	0.054308	0.052873
CT	N/A	0.032	0.174	0.071	0.024
PC	Cars/thousand persons	18.229	502.611	103.444	83.851
PB	Buses/thousand persons	1.280	94.370	11.837	10.369
PUA	m^2/person	2.270	72.870	15.868	8.800
PD	Persons/km^2	1914.290	39,871.801	7856.684	6953.921

The regression results of polycentric and urban commuting efficiency (represented by both CDI and MTS) are shown in the Tables 2 and 3. Each table shows six sets of regression results from the linear relationship between polycentricity and CDI or MTS. In turn, the models adopted a method of adding a control variable.

Table 2. Regression coefficients of CDI and polycentricity as well as control variables.

Variable	Model 1 (R^2 = 0.313)	Model 2 (R^2 = 0.352)	Model 3 (R^2 = 0.405)	Model 4 (R^2 = 0.461)	Model 5 (R^2 = 0.498)	Model 6 (R^2 = 0.513)
Polycentricity	−0.687 *	−0.697 *	−0.597 *	−0.622 *	−0.639 **	−0.547 *
CT		1.043	1.315 *	1.281 *	0.637	0.594
PC			4.949×10^{-4} **	2.890×10^{-4}	2.067×10^{-4}	3.623×10^{-4}
PB				2.655×10^{-3}	2.916×10^{-3}	2.783×10^{-3}
PUA					-6.42×10^{-6} ***	5.269×10^{-5} *
PD						0.003

*** denotes significant at 0.001; ** denotes significant at 0.01; * denotes significant at 0.05.

Table 3. Regression coefficients of MTS and polycentricity as well as control variables.

Variable	Model 1 (R^2 = 0.291)	Model 2 (R^2 = 0.327)	Model 3 (R^2 = 0.384)	Model 4 (R^2 = 0.421)	Model 5 (R^2 = 0.452)	Model 6 (R^2 = 0.499)
Polycentricity	14.218 *	14.547 *	14.606 *	15.005 *	15.446 *	14.066 *
CT		−33.704 *	−33.545 *	−33.007 *	−16.394	−15.743
PC			2.898×10^{-4}	0.004	0.006	0.003
PB				−0.042	−0.049	−0.047
PUA					1.676×10^{-4} ***	-1.491×10^{-4} **
PD						−0.042

*** denotes significant at 0.001; ** denotes significant at 0.01; * denotes significant at 0.05

The results of Models 1, 2, 3, 4, 5, and 6 show that polycentricity always has a significant negative relationship with CDI and positive relationship with MTS (significant at 0.05 level) regardless of the control variables. Thus, high polycentricity means low congestion index and fast average commuting speed. In Model 1, only the independent polycentricity index was analyzed using CDI and MTS. The results show that for every 1% increase in polycentricity, urban congestion coefficient decreases by 0.687%, whereas traffic speed increases by 14.218%. Polycentric spatial structure improves urban commuting efficiency.

In Model 2, the CT control variable slightly alters the effects of polycentricity on CDI and MTS. The promotion effect on MTS is enhanced by approximately 2.31%; the reduction effect on CDI, by 1.46%. Therefore, a compact spatial form can enhance the effects of polycentricity on commuter efficiency. Reasonable commuting distance improves the effectiveness of public transport in compact cities with controlled scales of urban development. Moreover, appropriate travel time, comfortable environment and cheap travel cost make public transportation an attractive and rational choice for urban dwellers. Several rules and policies can be promulgated to restrain the increase private cars and, thus, alleviate traffic pressure.

In Model 3, which has PC variables, the effect of polycentricity on CDI decreases with the influence of CT and PC. For every 1% increase in polycentricity, the reduction of CDI decreases from 0.697% of Model 2 to 0.597% of Model 3. On the contrary, the effect of polycentricity on MTS is enhanced. Ceteris paribus, the traffic speed increases from 14.547% to 14.606%. The improvement of the living standard of the residents results in an annual increase in car ownership and private car traffic. Families with cars are no longer constrained by traffic distance when choosing house locations, which accelerates the trend of suburbanization of living space. Loose and smooth traffic has been a main mechanism to improve the commuting speed of polycentricity. However, the increased number of vehicles entering the city would increase the possibility of traffic jams under the same number of commuting destinations (polycenters). Cars represent private travel, whereas PB (Model 4) represents urban public transport. Although the impact of PB on CDI and MTS does not have statistical significance, it enhances the effect of polycentricity on commuting efficiency. Compared with Model 3, the enhancement effect on MTS was increased by 2.73% and reduction effect on CDI was increased by 4.19%. Public transport has many advantages, such as wide coverage, large capacity, convenience and speed. The demand for passenger flow and the completion level of road facilities infrastructure in the suburbs is not similar to that of the main urban area. Public transportation mainly affects the commuting situation of the main urban area, where urban population centers (employment centers) are mainly distributed. Therefore, the promotion of public transport can improve the utilization rate of traffic resources, the congestion caused by too many cars and the speed of road traffic.

Urban commuter capacity is also related to the city's road facilities and population density. PUA and PD variables are added in the sequence, and Models 5 and 6 are constructed. The PUA variable increases the effect of polycentricity on the MTS, making it the largest among the six groups (15.446 in Model 5 > 15.505 in Model 4 > 14.606 in Model 3 > 14.547 in Model 2 > 14.066 in Model 6). However, after PD is added, the effect reaches minimum despite the effect of polycentricity on CDI and MTS. Complete road infrastructure is an important measure to promote urban commuting efficiency in a polycentric city. However, high population density makes frequent commuters to aggravate the pressure of urban commuting, resulting in unobstructed traffic and urban congestion.

To identify which factor can increase the effect of polycentricity, the change of polycentricity effect was observed by adding only one variable at a time (Table 4). Under similar conditions, the order of effect magnitude of polycentricity on MTS was PD > PC > CT > PUA > PB (absolute value indicates the effect magnitude, the same below). However, the order of effect magnitude of polycentricity on CDI was PD > PC > PB > CT > PUA. PC has the greatest positive effect on polycentricity, promoting MTS, with a 2.73% increase. On the contrary, PD has the most significant negative effect. It reduces the effect of polycentricity on MTS by 13.67%. In terms of the effect of polycentricity on CDI, PD most significantly increased the congestion index, whereas CT is the most significantly reduced congestion.

Table 4. Contribution of control variables to polycentricity and commuting efficiency.

Commuting Variables	CT	PC	PB	PUA	PD
MTS	14.218 -> 14.547 (0.309)	14.218 -> 14.606 (0.388)	14.218 -> 14.091 (−0.127)	14.218 -> 14.445 (0.227)	14.218 -> 12.274 (−1.944)
CDI	−0.687 -> −0.697 (−0.01)	−0.687 -> −0.597 (0.09)	−0.687 -> −0.661 (0.026)	−0.687 -> −0.696 (−0.009)	−0.687 -> −0.646 (0.041)

3.3. Compared with Previous Studies

Although the calculations indicate that polycentricity is statistically significantly greater than monocentricity in this study, we could not take the results for granted because it need to be scale and data specific. A careful comparison was made among the previous studies related to this topic, and conflicting results were found. The explanations for inconsistent conclusions could be summarized as follows:

(1) First, the study areas are inconsistent. Some of them are conducted within a city or a metropolitan area [15,18,60], While others take numerous cities rather a single city as study area [43]. Therefore, the results may or may not be the same with alternative research scales, and each result may only be applicable for the specific scale.
(2) Second, part of the explanation could be the inconsistent data source even for the same indicator. For example, Gordon et al. [28] and Cervero et al. [18] found different relationships between urban spatial form and commuting efficiency even though using the same indicator. This may due partially to the inconsistent data obtained from different national surveys. Further studies are needed to predict whether the results remain the same when using the same dataset.

Admittedly, city-wide data collecting is usually time-consuming and costly, and it is difficult to be applied extensively. The emergence of new urban data opens new opportunities of conducting multi-city analysis with the same dataset source at fine-grained scale. This study found positive and significant impact of polycentric urban form on urban commuting for 100 Chinese cities with the use of fined-grained geographic data, contributing to the literature in the main debate focusing on whether to support monocentric or polycentricity urban structures.

Fortunately, we found that all the existing studies aiming at Chinese cities have achieved the same conclusion that polycentric spatial structure helps to improve commuting efficiency even based on traditional socioeconomic data or new big data, and numerous cities [43] or a single city [61]. All the findings help to verify the necessity of the implementation of 'polycentric urban patterns' in China.

3.4. Reason for Polycentricity and Suggestions for Urban Planning

In urban planning and construction, people often overlook the importance of urban form. Only when the change of urban form seriously affects production, life and environment, can people find defects [56]. China's urbanization rate in 2016 was only 57.35% (National Bureau of Statistics, 2016). However, the '2013 China Human Development Report' released by the United Nations Development Program pointed out that China's urbanization will reach over 70% by 2030. Therefore, Chinese cities are expected to expand for a certain period [56]. Urban space will continue to undergo profound changes, which is both a challenge and an opportunity. The challenge is if Chinese cities can eliminate urban sprawl, which is likened to a 'spread the pie' around a single center. Meanwhile, the opportunity is to leave enough room to reshape urban form.

Currently, many cities in China are facing major urban diseases, such as overcrowding, traffic jams and high housing prices. In particular, the urban problems in the developed regions of Eastern China are quite serious. Unlike Western cities, China's cities generally have large populations. According to statistics from the National Development and Reform Commission in 2014, 142 Chinese cities have a population of over 1 million, of which six cities have a population of over 10 million. With such large populations, the mode of one or few centers leads to excessive concentration of resources. Moreover, commuters share a similar target area, which brings enormous commuting pressure in the downtown area and causes very large economic losses. Building new towns with mixed-use and encouraging people to work close to home in suburban areas can reduce the population and employment pressure from downtown, thereby solving commuting problem. International and domestic disputes on monocentric and polycentric cities remain unresolved. Even Cervero et al. [62], the strongest supporter of monocentric cities, acknowledged that the residents of the former central area who have moved to the employment area have a much shorter commuting time than those who still live in the central area. The main reason for such a disagreement is the mechanism under which a polycentric urban spatial structure will be formed. If subcenters realize the complementary function during formation that the residents can get close to the employment, then the polycentric urban spatial structure will undoubtedly reduce the volume of traffic gathered in the single center. Such a structure will shorten the commuting distance and time of residents. On the contrary, if residence and employment places occupy different locations of the city, then the interregional travel of the residents will exacerbate urban traffic. Therefore, a polycentric spatial structure must balance employment and residence. Future urban planning should consider the six following aspects:

(1) To guide population transfer: It could be reasonably inferred from the model results that excessive population density can significantly reduce the function of polycentric spatial structure in increasing commuting efficiency. Population agglomeration mainly results from unequal spatial distribution of social resources. Therefore, population distribution can be improved by promoting equal public utilities in different regions. Preferential policies, such as household registration and taxation, must also be implemented.

(2) To guide the city's compact development: Compact city can significantly reduce congestion. It is considered a smart growth model, which can greatly reduce the dependence on road traffic, especially private cars. Compact city alleviates road traffic pressure, consumption of oil and other resources, and air pollution [63–65]. The creation of a compact city can be encouraged by measures, such as development of landfills [56] and delineation of urban growth boundaries.

(3) To improve the urban public transportation system: A 1% increase in buses owned by 10,000 people increases MTS by roughly 2.73% and reduces CDI by approximately 4.19%. Public transport has substantial coverage and transport capacity. Therefore, establishing public transport system may alleviate urban transport problems in China. Public transportation must be developed around subcenters, between main centers and subcenters as well as between subcenters. A public transport oriented development model (TOD) is also suggested. A polycentric urban structure usually include the main center and the subcenters which take stations over radial public transport lines as core areas, forming orderly polycentric development.

(4) To strengthen road infrastructure: Model 6 reveals the significant role of PUA in exerting polycentricity on MTS. As the most basic municipal engineering, roads link production and living spaces. In addition to increasing capital investment, the government should consider improving the design of road network features. These features must be designed in a way that increases the degree of urban road area per capita network center in the area where people gather and shortens the road network distance between different network nodes.

(5) To promote rational consumption of cars: The mainstream mode of transport has important constraints and guidance on the structure and form of the city, and the transportation system shapes land use patterns. A large number of cars have caused serious traffic congestion and environmental pollution, which has led to a low-density spreading of the city as the wheels roll forward. The government can implement regulations to control private purchase and use of cars. Such regulations include license plate queuing measures implemented in Beijing and Shanghai, which have curbed the excessive increase of cars to a certain extent.

(6) Jobs-housing balance: Polycentric cities are favorable to short commutes only when they have a balanced number of jobs and resident workers in each center. Therefore, 'polycentrism' plans and policies is required to take into consideration jobs-housing balance, not only the number, but also the type of jobs and urban housing.

4. Conclusions

In the era of data explosion, research methods have advanced from traditional small data to big data. Research innovations provided by big and open data provide opportunities to conduct large or even national-scale analyses. The relationship between urban spatial structure and commuting efficiency has always been a research hotspot in urban planning and geography. In this paper, through the new data environment (Landscan, traffic travel big data report), we re-examined such a relationship. The choices of population centers are based on Landscan's identification of population clustering hotspots. LandScan breaks traditional administrative boundaries and provides refined observational scales for identifying the spatial distribution of population. The commuting report data based on mass position trajectory movement effectively provides more granularity and more information on individual behavior of urban residents. Such results are the reflection of objective phenomena in the real world. They overcome the problems of small samples and strong subjectivity existing in the traditional methods based on questionnaire surveys. We discuss the significance of polycentric urban structure in the choice of Chinese cities from the perspectives of population size, actual urban problems and the disputes between monocentricity and polycentricity. Several present findings are recommended for future formulation of urban planning policies, such as guiding population transfer, encouraging the compact development of urban cities, improving the urban public transportation system and regional jobs-housing balance.

The multiple linear regression model proves that polycentricity can significantly promote urban commuting efficiency. However, the relationships among variables are assumed to be homogenous before analyzing regression model, thereby hiding the local characteristics of such relationships. The results represent certain 'average' state of the study area, which ignores the spatial heterogeneity prevalent among variables. As a geographical unit, the city has its own laws of spatial and regional heterogeneity, that is, the variables have spatial nonstationary effects. After considering the spatial factors, the polycentric urban structure in a local city will not necessarily promote urban commuting efficiency. Therefore, the following study will continue to conduct in-depth research on this issue. Spatial variables will be introduced into the regression model to obtain a regional differentiation result.

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