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Research Article

Impact of Road Network Topology on Public Transportation Development

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Planning of road networks is fundamental for public transportation. The impact of road network density on public transportation has been extensively studied, but few studies in this regard involved evaluation indicators for connectivity and layout of road networks. With 29 cities in China as the study cases, this paper quantifies the layout structure of the road network based on the network's betweenness centralization and establishes a multivariate linear regression model to perform regression of the logarithm of the frequency of per capita public transportation on betweenness centralization. It is found in the present work that there is a significant correlation between the layout structure of an urban road network and the residents' utilization degree of public transportation. A greater betweenness centralization of the urban road network, namely a more centralized road network, means a higher frequency of per capita public transportation of urban residents and a higher degree of the residents' utilization of public transportation. In the development of public transportation, centralized and axial-shaped layout structures of road networks can be promoted to improve the utilization of public transportation.

1. Introduction

Amid rapid urbanization, the development of Chinese cities has received much attention from researchers worldwide. Looking back at the development of major cities around the world, we find that urbanization was often accompanied by the continuing centralization of population towards cities and the expanding scale of cities, which has resulted in such "urban malaise" as traffic congestion and environmental degradation [1]. With an increasing number of automobile ownership, China has surpassed the United States and risen to be the world's largest automobile market. As the supply-demand conflict in urban transportation grows stronger, traffic congestion has become one of the most serious social problems, and this also holds true in big cities in China. As a result, unsustainable development of urban transportation takes a toll on both economic growth and people's life.

It was reported that in the first quarter of 2021, about 59% Chinese cities were in a state of slow passage and 1.66% in a state of congestion in rush hours [2]. Traffic congestion not only wastes time but increases energy consumption and pollutes the environment. Optimizing public transportation is widely conceived as an effective solution to urban congestion, which can alleviate the energy pressure and environmental pollution caused by wide use of cars and help build a sustainable urban transport system. Under this circumstance, "prioritizing public transportation" has been proposed as the national strategy by the Chinese government. In addition, it was found that giving priority to the development of public transportation can effectively reduce the dependence of citizens on cars and achieve the purpose of alleviating traffic congestion [3].

However, it remains to be explored how to promote the development of urban public transportation, especially to increase the number of per capita public transportation. There are many factors affecting the frequency of per capita public transportation. Based on the travelers' pursuit of utility maximization of the choice, some scholars analyzed factors such as bus travel time, walking time, and waiting time [4]. Some explored the impact of factors related to social and economic development, such as GDP and vehicle ownership, on the frequency of per capita public transportation [5].

As the foundation of transportation, the road network plays a significant role in traffic management. If the traffic demand is fully considered in the stage of road network planning, it will have a profound impact on the entire traffic structure. Some existing studies have shown that a lower connectivity of a road network and less supply of public transportation will promote use of private cars [6]. Accordingly, a higher road network connectivity, an improved public transportation network, and pedestrian-friendly road network planning (spacious and high-quality walkway, as well as street furniture settings) will encourage residents to shift from walking to public transportation means like buses [7–10]. The "private car-oriented" road network system is no longer aligned with the needs of many developing cities in China and therefore hinders the development of public transportation. Since the urban public transportation system is based on the urban road network, the structure and form of the urban road network necessarily have impacts on public transportation. Some typical urban road networks, such as the finger-shaped road network, radial-circular road network, and grid road network, have different topological structures. Correspondingly, the planning of public transportation and the transport cost of these networks are inevitably different, which affects the choice of people's travel modes.

However, most existing works only analyze the relationship between the urban road network and public transportation from the perspective of the density of road network [11] but overlook the index that can evaluate the relationship of road connectivity with factors affecting public transportation. Studies on the layout structure of road networks often pay more attention to the measurement method [12] and characteristics [13–15] of road network topology, as well as the influence of the road network layout on the traffic efficiency and reliability of the traffic network [16], or the relationship between layout structure of road network and density of bus line network [17]. However, there are few studies on the relationship between layout structure of road network and urban public transportation. Since the impact of road network topology on public transportation has not been analyzed before, it is difficult to analyze its impact on public transportation in terms of the characteristics of the layout structure of the road network. Therefore, through regression analysis and quantitative research on 29 cities in China, we used the betweenness centralization to describe the characteristics of the layout structure of the urban road network and identified the relationship between the layout structure and public transportation of an urban road network. Some suggestions are also put forward for public transit-oriented urban development from the perspective of the layout structure of the road network.

2. Methodology

2.1. Definition of Road Network Layout Structure. Urban road networks often present regular structural characteristics, which reflect the combination of various interrelated factors in the network, including the overall form, arrangement mode, connection mode, and hierarchy of roads. Major structures of road networks include the hierarchical structure, the functional structure, and the layout structure [18]. The layout structure refers to the overall pattern and topology of a road network. The overall pattern describes the structure more intuitively. The main overall patterns include grid, radial, circular and radial, linear, and freestyle patterns, which are usually described with specific pictures or qualitative language; the topology of a road network shows the interrelationship between the basic units that make up the network and the relationship between the units and the whole network [19]. Road network topology is an abstract notion that describes the layout structure of a road network, which considers only the connection rules among the constituent parts and the structural characteristics of the entire network instead of the specific geometric attributes such as width and gradient of lane. Besides, the connection condition of roads such as connectivity, clustering, and centrality are considered. Connectivity describes the number of paths that can be selected between two points and the degree of direct reach. The clustering represents the aggregation degree of vertices in a road network. The centrality can describe the relatively important points and road segments in the road network. For example, the betweenness centrality can reflect the skeleton of the road network and the development model of the city [20]. The road network can be abstracted into a topological structure. The layout structure of the road network can be well quantified by constructing a topological structure model of the urban road network and then performing analysis with the help of the graph theory and complex network theory.

2.2. Relationship between structure of road network and public transportation system. In 1977, *Machu Picchu Charter* published by the International Institute of Modern Architecture proposed that "private cars should be subordinate to the development of the public transportation system in accordance with the policy of future urban transportation" [21]. In 1996, the *New Urbanism Association* proposed in *New Metropolitan Charter* that in contemporary metropolises, the motor vehicle traffic should adapt to the principle of encouraging public transportation and slow passage, which can only be achieved by the way of showing respect for walking and public space [22]. In order to flesh out the concept of new urbanism, many modes have been proposed, and the most representative one is transit-oriented development (TOD) [23]. Relevant studies have focused on the benefits of TOD in transport, environment, and other aspects through case analysis and summarized lessons from real-world cases, which prove the sustainability of the TOD development mode in urban development [24, 25]. After being introduced into China, public transportation planning strategies have greatly promoted the development of the road network structure because of the strategies' emphasis on urban road connection and coordinated development of land use and transport, which is conducive to alleviating the problem caused by expanded urbanization. As a result, traffic and environmental issues can also be solved through urban development guided by public transportation.

At present, studies on the layout structure of road networks mainly focus on structure optimization of road network, which is called the network design problem (NDP), involving two subproblems: continuous network design problem (CNDP) and discrete network design problem (DNDP). The former is to improve existing sections of roads, whereas the latter is to add new sections. Considering the road selection behavior of the traffic network users and budget constraints, these two types of optimization problems are aimed at minimizing the cost of entire transport system. Based on this, mathematical models and many algorithms describing the network design are proposed, among which are the linear optimization model and the random user equilibrium optimization model [26–28]. From the perspectives of the traffic function of the road network structure model and its adaptability to the traffic model, the road network structure model suitable for public transportation guidance is determined.

2.3. Application of Road Network Structure Agglomeration in the Layout Structure of Road Network

2.3.1. Brief Introduction to Complex Network Theory. Most existing works on structural analysis of road networks employ the graph theory-based network models, in which the complex network model is more commonly used [29]. There are many nodes in the road network of a city, and in this logic, the urban road network can be considered a complex network. To study the structural characteristics of complex networks, a mathematic tool called "graph" is often used to describe such networks. A complex network is a system in which several nodes are combined into a connected whole. The graph theory uses some abstract points to represent the nodes in the specific network. The connection relationship between the nodes in the network is represented by lines connecting the nodes. When the graph theory is applied to the urban road network, each intersection is regarded as a node, and each road as a line in the network. In 1936, the first monograph on the graph theory was published, which led to rapid development of this theory. In the 1960s, Paul Erdos and Alfred Renyi proposed the random graph theory, which started a systematic study of the complex network theory. At the end of the 20th century, as new models such as the small world model and the scale-free network were proposed, the complex network theory was no longer limited to mathematics. Empirical research has been performed to analyze topological characteristics of real networks, including networks in fields of physics, biology, information management, and transport [30, 31]. Among them, the research on road networks covers many aspects, such as the geometrical properties, structural characteristics, formation mechanism, and evolution law of the network. There are many basic statistical indicators for road network research, the most important of which include the shortest path, average distance, aggregation coefficient, and betweenness [32]. It was found that the urban road network shares the many characteristics with the small world network and scale-free network [33, 34].

2.3.2. Construction Method of Road Network Topology. By the abstraction way, the construction methods for road network topology are mainly divided into the primal approach and the dual approach [35, 36]. The former abstracts the nodes of the road network (such as road intersections and interchanges) into vertices and the connection lines between nodes into edges, whereas the dual approach abstracts the connection line between nodes into points and abstracts the nodes into edges [37].

2.3.3. Betweenness Centralization and Its Calculation Method. Betweenness can also be called intermediateness, which is an indicator to measure the centrality of nodes in a network. The betweenness of a node refers to the proportion of the number of shortest paths passing through this node to the total number of shortest paths in the network. It is a global variable that reflects the role and influence of the corresponding node or edge on the entire network. A larger value of betweenness indicates more importance of the node in the network. Thus, calculating the betweenness of a node in a road network is of practical significance. Freeman [38] used the index of betweenness centralization of a road network to evaluate the aggregation degree of the road network topology. The network centralization includes closeness centralization, degree centralization, and betweenness centralization [39]. Among them, betweenness centralization (C_B) can better describe the degree of road network agglomeration, and hence, it is selected as the index of the road network structure agglomeration.

The betweenness centralization can reflect the centralization level of the overall network. It is the ratio of the sum of the betweenness centrality of the most core point and the difference values of the betweenness centrality of other points in a network to the most possible difference value. It is widely used in studies on social networks, industrial clusters, transport, and other fields [40–42]. The calculation formula is as follows:

$$C_B = \frac{\sum_{i=1}^{N} \left(C_{i^*,B} - C_{i,B}\right)}{N^3 - 4N^2 + 5N - 2}. \tag{1}$$

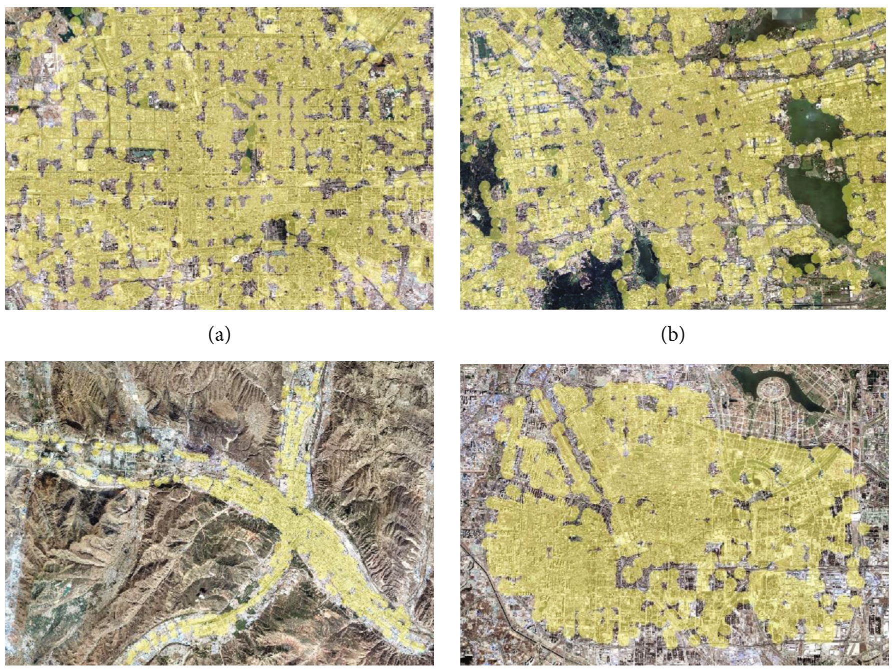
In the formula, i refers to the serial number of a node, N refers to the quantity of nodes in the complex network, $C_{i,B}$ refers to the betweenness centrality of the node, and i^* refers to the node with the largest value of the betweenness centrality. Betweenness centrality ($C_{i,B}$) represents the possibility of a node located in the shortest path of any two other nodes in the network, that is, the extent to which a node can be located in the "middle position" of other nodes in the network. The calculation formula of $C_{i,B}$ is as follows:

$$C_{i,B} = \frac{1}{(N-1)(N-2)} \sum_{\substack{j,k \in N \\ j \neq k; j,k \neq i}} \frac{n_{jk}(i)}{n_{jk}}, \tag{2}$$

where N refers to the quantity of nodes in the complex network, n_{jk} refers to the quantity of the shortest paths between node j and node k, and $n_{jk}(i)$ refers to the quantity of the

Table 1: Topographic index of cities studied in the present work.

City type	City name	Topographic index
Cities with less undulating terrain	Beijing, Harbin, Haikou, Hefei, Hohhot, Nanjing, Shanghai, Shenyang, Shijiazhuang, Taiyuan, Tianjin, Changchun, Zhengzhou	0
Cities with moderately undulating terrain	Nanchang, Ningbo, Qingdao, Xiamen, Suzhou, Xi'an	1
Cities with highly undulating terrain	Chengdu, Dalian, Kunming, Lanzhou, Luoyang, Nanning, Shenzhen, Xining, Yinchuan, Changsha	2



(a) (b) (c) (d)

Figure 1: The 300 m service area of bus stations in part of cities studied. (a) Beijing. (b) Suzhou. (c) Xining. (d) Zhengzhou.

shortest paths between node j and node k passing through node i [42].

2.3.4. Application of Pajek. For analysis and visualization of large networks with thousands and millions of nodes, Pajek is a common but complex analysis tool widely used in analysis of social networks [43, 44], genealogy [45], network analysis [46], aviation networks [47], power grid [48], etc. One of its data objects is "Networks" data with the expanded name of .net. When generating a "Networks" file, we need to enter the name of each node and edge of the network (represented by the serial number of the nodes at both ends of the edge).

The geometric network constructed by ArcGIS can display the serial number of each node. By inputting the nondirectional connection line between the nodes into Pajek, we can calculate the betweenness centralization (C_B) and obtain the analysis chart of the network.

3. Results

Based on the betweenness centralization, an index that reflects the road network layout structure and the development of public transportation, that is, the number of per capita public transportation, this paper establishes a model and performs a case study on 29 cities in China at the prefecture level and above. Development degrees of social economy, public transportation, and the topographical conditions may partly decide people's choice of travel mode. Therefore, in addition to analyzing the index of road network topology, the empirical analysis should also take into account of the status of economic development, the supply of public transportation, the relevant indicators of the road network, the urban topographic conditions, and the built-up area. However, the errors or disturbances caused by factors such as the size of the cities and investments into public transportation should be excluded, and related variables should be controlled. Thus, the regression of the number of public transportation per capita on the layout structure of the urban road network is obtained, and their relevance is revealed.

3.1. Establishment of the Model

3.1.1. Selection of Explanatory Variables. There are many factors affecting residents' use of public transportation, such

Table 2: Variable description.

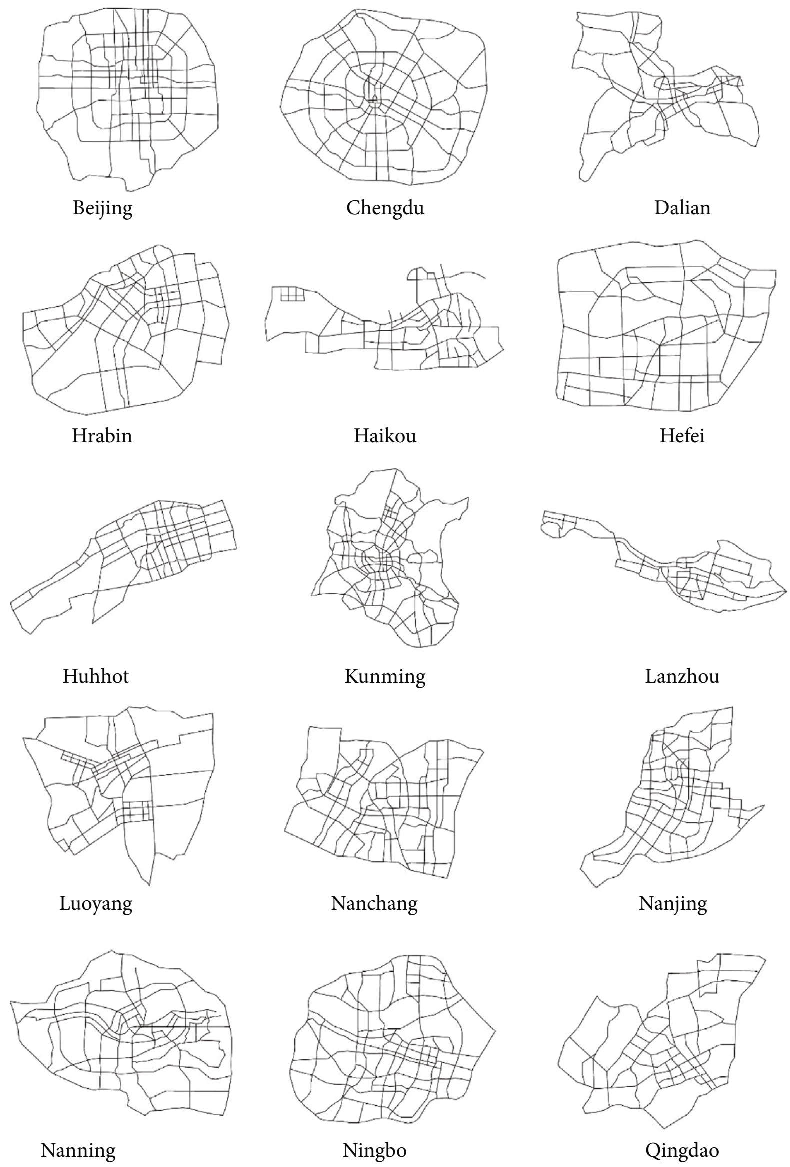
Variables	Description
y_p	Frequency of per capita transit trip in a year
BC	Betweenness centralization
GDP_{pr}	Per capita GDP (unit:10,000yuan)
m_{bo}	Number of public transportation vehicles per 10,000 people
A_{pr}	Per capita urban road area (unit: m^2)
f_{ai}	Urban investment in fixed assets (the generic terms of the workload expressed in monetary terms of building and buying fixed assets in a certain period and related cost) (unit: 100 billion Yuan)
t	Topographic index
S	City scale (unit: km^2)
c	Coverage ratio of area within 300 m from bus stations (the area within 300 m from bus stations divided by the urban built-up area)

as the time and distance of travel (average travel time), land utilization (land utilization mixedness, building density, etc.), road design (density of road network, average width of road, etc.), bus supply (density of bus station, density of bus line network, etc.), and socioeconomic attributes [49]. Since the research in this paper focuses on the large-scale comparison among multiple cities, the betweenness centralization (C_B) of the urban road network is selected as an indicator to measure the characteristics of urban street patterns, and per capita GDP (GDP_{pr}) is used to indicate the economic development of the city. The numbers of public transportation vehicles per 10,000 population (m_{bo}) and 300 m bus stations coverage ratio (c) both reflect the bus supply of the city. Per capita urban road area (A_{pr}) and urban investment in fixed assets (f_{ai}) are used to represent the urban built environment. Considering that the slope of the terrain may have an impact on the travel mode in the city, the topography (t) of the city is added into the model as an explanatory variable. Specifically, 0, 1, and 2 are used to represent cities with less undulating terrain, cities with moderately undulating terrain, and cities with highly undulating terrain, respectively. Since the scale (S) of the city has a significant impact on the distance of travel, thus significantly influencing the structure of urban transportation, the city scale is therefore introduced into the model (indicated by the area of land used for urban construction). Of course, to some extent, the betweenness centralization (C_B) will also reflect the built environment characteristics of the urban scale such as urban spatial structure or urban morphology. At the same time, to avoid problems that the multicollinearity problem might incur in regression, the authors avoid autocorrelation in the selection of independent variables.

Table 3: Variable data of studied cities.

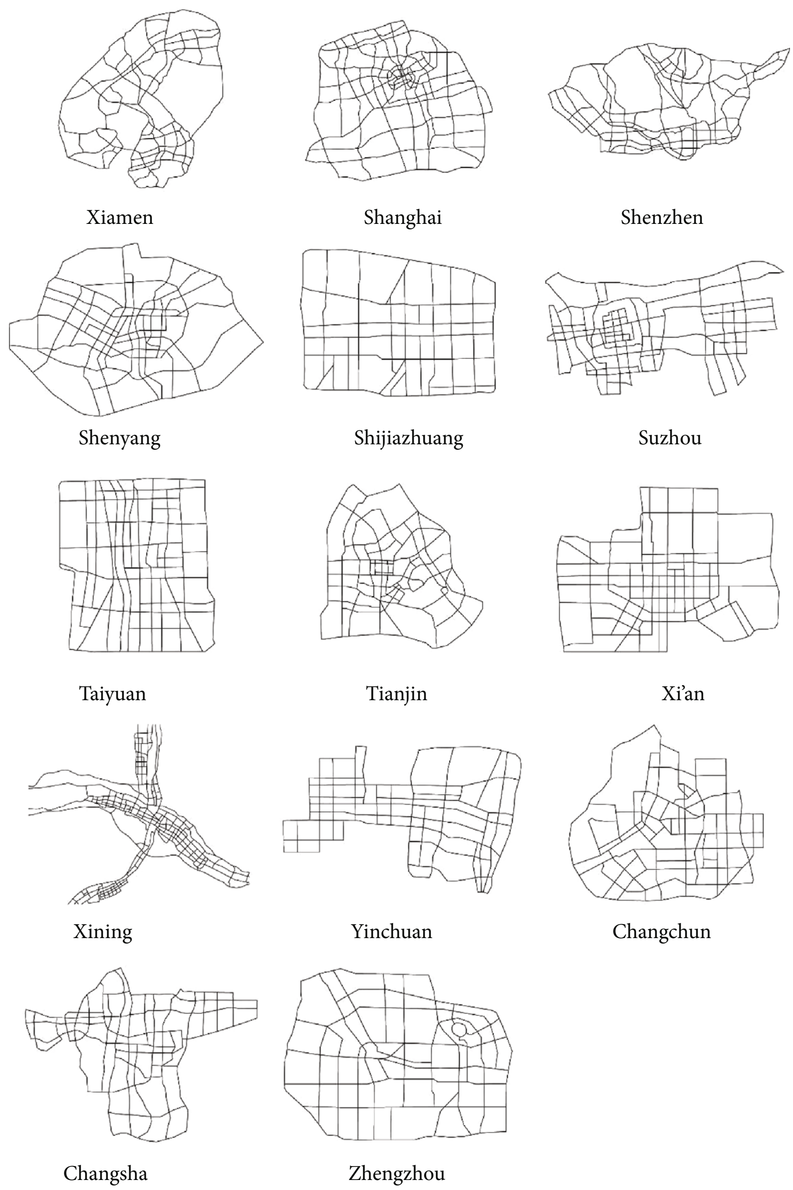
City	y_p	m_{bo}	GDP_{pr}	A_{pr}	f_{ai}	t	S	c
Beijing	389	18.95	15.43	7.72	6.75	0	1306	0.62
Chengdu	291	18.01	11.47	13.18	3.90	2	529	0.67
Dalian	348	16.72	16.31	14.48	4.31	2	396	0.41
Harbin	250	12.65	6.83	10.04	3.84	0	391	0.69
Haikou	190	9.95	5.55	8.98	0.65	0	124	0.56
Hefei	281	16.01	12.77	22.72	3.12	0	393	0.69
Hohhot	283	29.25	15.87	17.41	0.97	0	230	0.63
Kunming	308	17.76	9.77	14.26	2.08	2	397	0.51
Lanzhou	307	10.91	6.04	11.78	0.86	2	207	0.57
Luoyang	149	8.84	6.34	11.74	0.74	2	192	0.50
Nanchang	267	15.39	9.98	15.28	2.01	1	250	0.46
Nanjing	166	10.80	12.46	19.84	5.09	0	713	0.60
Nanning	196	9.69	7.21	12.61	1.73	2	283	0.60
Ningbo	210	19.75	18.90	12.61	1.93	1	295	0.45
Qingdao	276	16.86	14.07	21.45	2.76	1	470	0.68
Xiamen	457	19.72	15.32	18.14	1.34	1	282	0.61
Shanghai	199	12.25	15.64	7.28	5.64	0	999	0.72
Shenzhen	848	98.53	46.77	37.03	2.50	2	871	0.66
Shenyang	219	10.50	11.09	14.82	5.06	0	455	0.61
Shijiazhuang	253	18.04	6.76	18.07	1.90	0	217	0.64
Suzhou	191	13.50	19.88	24.05	3.07	1	441	0.54
Taiyuan	193	9.91	7.79	12.53	1.48	0	320	0.54
Tianjin	166	11.77	15.99	15.14	8.46	0	736	0.71
Xi'an	300	14.00	7.05	12.09	4.39	1	424	0.68
Xining	330	15.21	5.55	7.15	0.60	2	85	0.52
Yinchuan	291	18.79	7.71	17.77	0.47	2	149	0.48
Changchun	201	12.98	9.81	18.58	2.66	0	452	0.48
Changsha	247	13.89	15.07	10.01	2.69	2	326	0.45
Zhengzhou	200	11.11	6.45	7.42	2.50	0	383	0.68

3.1.2. Model Construction. In this paper, the frequency of per capita public transportation (y_p) is used as the explained variable to construct the multivariate linear regression model. Since the explained variable y_p is relatively larger than the independent variable, in order to assign the independent variable C_B (i.e., the betweenness centralization) with a proper meaning, the logarithmic processing of explained



(a)

Figure 2: Continued.



(b)

Figure 2: The original maps of road networks of cities studied.

variable is performed, namely constructing a semielastic model:

$$\ln y_p = \beta_0 + \beta_1 C_B + \beta_2 GDP_{\text{pr}} + \beta_3 m_{\text{bo}} + \beta_4 A_{\text{pr}} + \beta_5 f_{\text{ai}} + \beta_6 t + \beta_7 S + \beta_8 c + \mu, \quad (3)$$

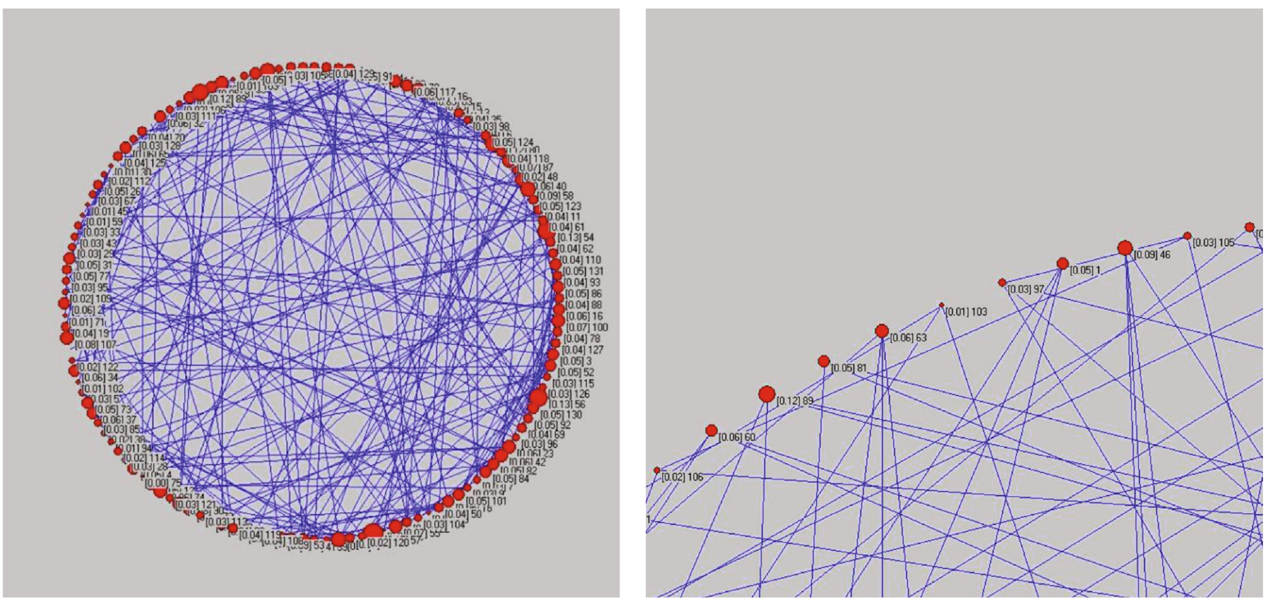
where β_0 refers to the intercept parameter of the semielastic model, β_1-β_8 are the slope parameters of the model, and μ refers to the error term of the model.

3.2. Research Data and Processing

3.2.1. Selection of Case Study Cities and Source of Data. The purpose of this paper is to analyze the impact of the layout structure of the urban road network on public transportation. Therefore, the layout structure of the road network of selected research objects should be representative, and the development of urban public transportation should be more balanced. In the present work, a total of 29 municipalities, including Beijing, Shanghai, Shenzhen and Lanzhou, some provincial and subprovincial cities, and prefecture-level cities, are selected for research. Among them, Lanzhou is a typical linear-shaped city due to the terrain limitation, and the layout structure of its road network also shows a typical linear-shaped distribution. Shenzhen features a linear pattern in terms of urban morphology, and the organization and layout of its road network are therefore a linear one. As for Beijing, the main urban area is steeped in history, and the layout structure of road network features a square-grid structure. Chengdu shows a relatively obvious circular-radial road network, whereas Shanghai has a freestyle road network.

Table 4: Betweenness centralization of cities studied.

City	C_B	City	C_B	City	C_B
Lanzhou	0.231591	Qingdao	0.142179	Yinchuan	0.164094
Shenzhen	0.228655	Hohhot	0.140267	Changchun	0.160323
Xining	0.225887	Ningbo	0.132651	Haikou	0.152036
Nanchang	0.189090	Hefei	0.131271	Suzhou	0.151685
Shijiazhuang	0.188926	Nanning	0.127353	Shanghai	0.146765
Xiamen	0.188101	Nanjing	0.108786	Changsha	0.143728
Dalian	0.184861	Beijing	0.107189	Luoyang	0.092967
Taiyuan	0.180529	Chengdu	0.097408	Tianjin	0.090337
Kunming	0.173238	Xi'an	0.094943	Zhengzhou	0.084134
Harbin	0.079269	Shenyang	0.076542		



(a) (b)

Figure 3: (a) The topological structure of Beijing's main road network (global view). (b) The topological structure of Beijing's main road network (partial enlarged view).

Part of the data of the explained variables and explanatory variables of the model are obtained from *China Urban Statistical Yearbook* (2018) (such as y_{p}, $\mathrm{GDP}_{\mathrm{pr}}$, m_{bo}, A_{pr}, f_{ai}, and urban scale), and some are obtained based on terrain and landform and data processing of Baidu Map POI (Point of Interest). For example, according to the topography, cities can be divided into three types including cities with less undulating terrain, cities with moderately undulating terrain, and cities with highly undulating terrain. The topographic index is represented by the value of 0, 1, and 2 (Table 1). Based on the POI data of the bus stations in each city, we build a buffer zone of 300 m (Figure 1) with the bus station as the center and use the ratio of the area of buffer zone to the area of the municipal district as the coverage rate of 300 m service area of the bus station. Tables 2 and 3 present the descriptions and specific values of variables of each city studied in the present work.

3.2.2. Construction of Topology of Road Network. Since the primal approach of construction of topology of road network is simple, intuitive, and consistent with the actual experience of people in real life, it is adopted in this paper. Firstly, the satellite images and street maps of cities studied are extracted by Google Earth. The main and secondary roads within are vectorized by the AutoCAD software, and the results can then be imported into the ArcGIS software. The original road map of the road network of cities studied (Figure 2) can be obtained by utilizing utility network analysis to build the geometric networks of the road networks.

3.2.3. Calculation of Betweenness Centralization. The geometric network constructed by ArcGIS displays the serial number of each node. By inputting the nondirectional connection line between the nodes into Pajek, and calculating the betweenness centralization, we can obtain the C_B of the

Table 5: Summary statistics.

Variables	Mean value	Standard deviation	N
y_p	276.0689655	130.8215609	29
C_B	0.144521	0.0440948	29
GDP_{pr}	17.646207	16.1521753	29
m_{bo}	12.410124	7.9024728	29
A_{pr}	14.971724	6.2851197	29
f_{ai}	2.8798000	1.9588289	29
t	0.8965517	0.8845349	29
S	424.6896552	272.4855309	29
c	0.58	0.09	29

Table 6: Regression result of OLS estimation.

Variable	Coefficient	Std. error	T -statistic	Prob.
β_0	4.591675	0.476547	9.635313	0
C_B	2.805508	1.299683	2.158609	0.0432
GDP_{pr}	-0.016086	0.015958	-1.007994	0.3255
m_{bo}	0.019937	0.007311	2.726831	0.013
A_{pr}	-0.004846	0.011052	-0.438522	0.6657
f_{ai}	0.035709	0.04814	0.741776	0.4668
t	0.085258	0.05927	1.438481	0.1658
S	$9.56E-05$	0.000339	0.282233	0.7807
c	0.429148	0.66719	0.643216	0.5274
R-squared	0.700749	Mean dependent var		5.549815
Adjusted R-squared	0.590257	SD dependent var		0.353421
SE of regression	0.226228	Akaike info criterion		0.114584
Sum squared resid	1.023587	Schwarz criterion		0.538917
Log likelihood	7.338538	Hannan-Quinn criterion		0.247479
F-statistic	6.041949	Durbin-Watson stat		0.916533
Prob (F-statistic)	0.000523			

road network of each city studied (Table 4). The analysis charts of Pajek are shown in Figure 3. The red dots in the figure represents road nodes, and the size of the dot indicates their betweenness centrality ($C_{i,B}$), which is also specified by the values in square brackets; values outside the square brackets represent the name of the node.

Figure 3 and Table 4 show that the C_B of linear cities and radial cities (such as Lanzhou, Shenzhen, and Xining) are higher than those of circular and grid cities (such as Beijing and Shenyang).

3.3. Regression Analysis

3.3.1. Summary Statistics. Summary statistics for regression analysis are shown in Table 5.

3.3.2. Result of Regression Analysis. The OLS (ordinary least square) estimation method is employed to estimate the above model, and the estimated values of each coefficient and related statistics are obtained, as shown in Table 6.

The formula is

$$\ln \mathrm{yp} = 4.59 + 2.81C_B - 0.02GDP_{pr} + 0.02m_{bo} - 0.005A_{pr} + 0.04f_{ai} + 0.08t + 0.0001\mathrm{S} + 0.43c, \tag{4}$$

$N = 29$, $R^2 = 0.59$.

The F test of the model is significant, and the imitative effect is good, which is of statistical significance. As shown in the result of regression analysis, there is a significantly positive correlation between the betweenness centralization (C_B) and per capita public transportation (y_p) with a confidence of 95%, that is, the frequency of per capita public transportation increases with the increase of C_B of an urban road network. When the significance level is 5%, the probability P of the C_B is 0.0432, and the coefficient is 2.81, which indicates that under this model, for every 0.1 increase in C_B, the y_p will increase by 28.1%.

According to the analysis result, when the variables such as GDP_{pr}, m_{bo}, c, A_{pr}, f_{ai}, and t remain unchanged, cities with a linear or radial road network have a higher frequency of per capita public transportation than cities with a grid road network or a circular road network. In other words, radial road networks may be more conducive to the development of public transportation than the grid one.

4. Discussion and Conclusion

With 29 cities in China as the study cases, a multivariate linear regression model is established to estimate the impact of the layout structure of urban road networks on residents' utilization of public transportation. With other factors controlled, the results show that there is a significant correlation between the layout structure of an urban road network and residents' utilization of public transportation. A greater betweenness centralization means a more centralized road network and more per capita transit trips for urban residents, which contributes to a higher degree of utilization of public transportation by the residents.

There are many factors affecting public transportation, including the development of urban economy and public transportation, vehicle ownership, city scale, and urban topography. In addition, the betweenness centralization is also an important factor affecting the frequency of per capita transit trip. The reasons are as follows. On the one hand, a linear and radial road network facilitates traveling between the central area of the city and the surrounding suburbs, as well as the traffic among the city groups, which is beneficial to the organization of bus routes. Based on several main nodes, building a layout model of a road network makes it more convenient to plan transfers in public transportation, which can reduce the operating cost of public transportation and improve the bus service. In addition, the strip-shaped cities are mostly large cities with and undulating fluctuations, complex terrain, and large slopes, which are not suitable for bicycle travel. Therefore, the use of public transportation is promoted. As for a grid road network, there is a high repetition rate of public bus routes. Therefore, public transportation is difficult to organize, and passengers have to transfer more times. In addition, excessive intersections are likely to cause congestion and hence result in bad bus-riding experience. On the other hand, compared with a radial road network, a grid road network has better connectivity, accessibility, and flexibility, which promotes the development of private cars. However, as the radial roads show less accessibility for traveling in the tangential direction, private cars may have a higher cost than, or the same cost as, buses, and hence, public transportation is preferred.

Therefore, as for transit-oriented urban planning, it is not wise to blindly improve the density and connectivity of an urban road network. Based on the layout structure of the road network, it is advisable to lay out an axial and radial road network to facilitate the development of public transportation and hence enhance the frequency of residents' utilization of public transportation.

Data Availability

The data used to support the findings of this study were supplied by the corresponding author under license and so cannot be made freely available. Requests for access to these data should be made to the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Conceptualization was done by C.M. and X.J.; methodology was done by C.M.; investigation was done by C.M. and W.F.; writing—original draft preparation— was done by C.M.; writing—review and editing—was done by C.M. and Y.M.

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