Complex network characteristics of the planned subway station network in Hangzhou (2005-2022)

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Abstract. The complex network characteristic of the planned subway station system is of great significance to the centrality layout of the existing urban areas. The three phases of the Hangzhou subway plan from 2005-2022 are selected as a case, and the complex network analysis method is used to study the centrality characteristic of the planned subway station system. The study found that with construction, the network density, clustering coefficient, average shortcut distance, all centrality indicators of the network gradually decreased; but in phase III adjustment, the average shortcut distance, three centrality potential indicators have all rebounded substantially. The newly-added airport rail express line has greatly increased the overall cohesion of the original subway network. The subway station networks of five planning stages all have smaller clustering coefficients and larger average shortcut distances, but none of them have a small-world characteristic, and the scale-free characteristic is still not obvious.

1 Introduction

As an effective urban development model for the coordinated development of transportation and land use, Transit-Oriented Development (TOD) has attracted the attention of many countries in the world and has been carried out active practices. However, many urban managers often lack overall strategies in the spatial development of metropolitan areas, especially in the urban spatial structure, land use, and public transportation integration [1]. Since we hope to see the effect of policy implementation soon, we pay more attention to the rapid construction of public transportation infrastructure to solve mobility problems, while neglecting the integration with land use to guide the sustainable and livable development of the city [2]. Hangzhou urgently needs to conduct targeted research on its urban space environment in response to the requirements of TOD, so as to realize the coupling of the built environment and large-scale public transportation.

As a theory describing the interrelationship of nature, society, and engineering technology, the complex network method provides a new perspective for studying the structural characteristic and functioning laws of real network systems. The central feature is the research focus of complex network analysis, which reflects the importance of the role played by individuals in an organization or system. Many researchers have abstracted road systems, public transportation systems, subway systems, etc. into complex network models, and developed several studies, such as structural features [3-4], central features [5-6], and land use and urban economic activities [6-8]. Li Jin et al. [3], Zhang Tieyan et al. [4]

studied the complexity and scale-free characteristic of subway networks; Huang Yong et al. used complex network analysis methods to analyze the overall, partial, and individual structural characteristic of the complex network of public transportation [5]; Paolo Crucitti et al. studied the centrality and statistical distribution characteristic of the transportation network of 18 cities in the world [6]; Wang Fahui, etc. studied the relationship between the transportation centrality of Baton Rouge and land use density in the United States [7]; Sergio Porta et al. studied the central characteristic of the Barcelona transportation system [8]. The above research reveals the character of the complex network of the transportation system and its interaction with urban land use from different levels and provides an important reference for people to deeply understand the coupling mechanism of public transportation and the built environment.

However, it should be pointed out that the existing research is more focused on the road system, while the research on the subway station system is insufficient. This study selects the three phases of the Hangzhou subway plan from 2005-2022 as a case study, using complex network analysis methods to study the centrality characteristic of planned subway stations based on topological network structure, which will help the making decisions based on the TOD development advantages, potentials and differences and provide a scientific basis for the formation of an urban organic renewal strategy at the stage of stock optimization.

2 Research methods

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2.1 Research objects and scope

This study selects all the stations of the Hangzhou Metro Planning Phase I to III from 2005-2022 as the research cases. The data used is based on 4 documents: ‘Engineering Feasibility Study Report of Hangzhou Metro Line 1’, ‘Hangzhou Metro Urban Rail Transit Recent Construction Plan (2013-2019)’, ‘The National Development and Reform Commission's Reply on the Third Phase Construction Plan of Hangzhou Urban Rail Transit (2017-2022)’, ‘the National Development and Reform Commission Reply to the Adjustment of the Third Phase Construction Plan of Hangzhou Urban Rail Transit (2017-2022)’. The research scope covers the urban areas to which all three phases subway lines will extend, from Laoyuhang in the west, Great Jiangdong New Town in the east, Hangzhou Ring Expressway South Line in the south, and Linping in the north. The total mileage of Hangzhou's planned urban rail transit network in the recent future is 423.5 kilometers, and the third phase of subway construction is 387.8 kilometers. As of April 2020, Hangzhou Metro has completed Metro Line 1, Metro Line 2, Metro Line 4 Phase I, and Metro Line 5 Phase I, and all of them have been achieved network operation (Table 1).

Table 1. Overview of the first to third planning phases (from 2005 to 2022) of Hangzhou subway network

Stage	Code	Include line	Num. of stations
Phase I	101	Line 1, Phase I of Line 2	56
Current phase (2020)	102	Line 1, Line 2, Phase I of Line 4, Phase I of Line 5	91
Phase II	201	Line 1, Line 2, Phase I of Line 4, Phase I of Line 5, Phase I of Line 6	107
Phase III	301	Line 1-10	224
Phase III (ADJ)	302	Line 1-10, Line 3 adjustment, Line 5 adjustment, Airport Express	237

2.2 Network model construction and polycentricity evaluation method

The establishment of the subway network model uses the Space L method. This method regards subway stations as nodes. If two stations are adjacent to each other on a subway line, then they are regarded as having a connection.

Indexes such as betweenness centrality potential, closeness centrality potential, degree centrality potential are important indicators to measure the centrality of the overall network (Table 2). UCINET software can measure the network centrality characteristic, which was developed by Stephen Borgatti, Martin Everett, and Linton Freeman of the University of California, Irvine.

Table 2. Meanings of centrality indicators

Indicators	Meaning
Betweenness centrality potential	The betweenness centrality of the overall network
Flow betweenness centrality potential	The flow betweenness centrality of the overall network
Closeness centrality potential	The closeness centrality of the overall network
Degree centrality potential	The degree centrality of the overall network

3 Research results

3.1 The basic characteristics and centrality characteristics of the network

Fig.1. Changes in centrality potential characteristics between five planning stages of Hangzhou subway network

According to the phased plan, the number of subway lines and stations is gradually increasing. From the first phase to the phase III adjustment, the overall subway network has increased from 2 to 11 lines, and the number of stations has increased from 56 to 237. In this process, the network density and clustering coefficient indicators gradually decreased; while the average shortcut distance gradually increased, but there was a substantial decrease in the 5th phase (Figure 1, Table 3). The betweenness centrality potential, flow betweenness centrality potential, closeness centrality potential, degree centrality potential all show a gradual decrease with the progress of stages. However, in the phase III adjustment, in addition to the flow betweenness centrality potential, the other three centrality potential indicators all showed a significant increase, of which the intermediate central potential and the close to betweenness centrality potential and closeness centrality potential increased significantly (Figure 2).

Table 3. Basic characteristics and centrality characteristics of Hangzhou subway network

Stage Code	Num. Of Nodes	Network Density	Ave. Shortcut Distance	Clustering Coefficient	Betweenness Centrality Potential	Flow Betweenness Centrality Potential	Closeness Centrality Potential	Degree Centrality Potential
101	56	0.0364	12.673	0.016	41.48%	41.51%	7.57%	3.77%
102	91	0.0227	13.343	0.010	27.00%	30.54%	6.79%	2.22%
201	107	0.0199	13.680	0.009	24.54%	28.98%	6.25%	1.81%
301	224	0.0100	14.598	0.003	20.84%	16.53%	5.88%	1.70%
302	237	0.0097	12.966	0.003	27.77%	9.90%	8.32%	2.01%

Table 4. Characteristics of complex network of Hangzhou subway network

Stage code	Num. of nodes	Num. of links	Ave. degree	Clustering coefficient			Ave. shortcut length			Complex network attributes		
				Random network C_{ran}	Actual network C_{real}	Regular network C_{reg}	Random network L_{ran}	Actual network L_{real}	Regular network L_{reg}	Small world quotient	Small-world	Scale-free
101	56	56	2	0.036	0.016	0.750	5.807	12.673	14.000	0.205	no	Not obvious
102	91	93	2.044	0.022	0.010	0.750	6.310	13.343	22.260	0.211	no	Not obvious
201	107	113	2.112	0.020	0.009	0.750	6.250	13.680	25.331	0.208	no	Not obvious
301	224	251	2.241	0.010	0.003	0.750	6.707	14.598	49.978	0.138	no	Not obvious
302	237	271	2.287	0.010	0.003	0.750	6.610	12.966	51.815	0.158	no	Not obvious

3.2 Complex network characteristics

A complex network refers to a network with some or all of the properties of self-organization, self-similarity, attractor, small world, and scale-free. Its main characteristics include small-world, scale-free, and other characteristics. The small-world characteristic reflects the convenient connectivity of complex networks with a large number of nodes and the average shortcut distance is small; while the scale-free characteristic reflects the serious heterogeneity of complex networks, and a small number of nodes often have a large number of connections while most of the nodes have few connections. The degree distribution of the nodes conforms to the power-law distribution. The comparison method of Watts et al. [9] and the Small Worlds Quotient method of Davis et al. [10] can be used to determine the small world attributes of the network. The subway network models in the five planning stages all satisfy $L_{real} < L_{ran} < L_{reg}$, but none of them satisfy $C_{ran} < C_{real} < C_{reg}$; at the same time, the small world quotient is far less than 1 (Table 4). Therefore, none of the subway networks models in all the planning phases has small world characteristic.

Regarding the scale-free characteristic, it can be determined by using the cumulative probability distribution of each node and the natural logarithm distribution of the cumulative probability of each node. In double logarithmic coordinates, the power-law distribution is represented by a straight line whose slope is the power exponent. Taking the phase III adjustment of

the subway plan (Phase 302) as an example, the fitting coefficient of the fitting equation of the cumulative point probability distribution of the overall network is 0.8445 when the power-law distribution is considered. And the fitting coefficient is 0.9129 when the polynomial distribution is considered.

Fig.2. Scale-free judgment of Hangzhou subway network in the phase III adjustment

At the same time, the fitting coefficient of the fitting equation of the natural logarithmic distribution of the cumulative point degree probability is 0.8445 when

considering the linear distribution. And the fitting coefficient is 0.9713 when considering the polynomial distribution. The above results indicate that the cumulative point-degree probability distribution of the overall network during the phase III adjustment is closer to a polynomial distribution than a power-law distribution (Figure 3). At the same time, the long tail phenomenon is not obvious from the distribution of actual points. Therefore, the scale-free nature of the subway network at this stage is not obvious. In the same way, the scale-free characteristic of the other four stages is not obvious.

Compared with the Beijing, Guangzhou, and Shanghai subway networks as of the end of 2011, although the subway network of Hangzhou has a similar scale, it has a larger average degree, a shorter average shortcut distance, and a larger average clustering coefficient which show a better network characteristic (Table 5).

Table 5. Comparison of Hangzhou subway network with subway network of Beijing, Guangzhou and Shanghai

City	Num. of Nodes	Num. of Edges	Ave. Degree	Ave. Shortcut Distance	Ave. Cluster Coefficient
Beijing (2011)	172	185	2.15	14.4	0
Guangzhou (2011)	122	126	2.07	14.6	0
Shanghai (2011)	244	269	2.21	14.9	0.0008
Hangzhou (Phase I)	56	56	2	12.7	0.016
Hangzhou (2020)	91	93	2.04	13.4	0.010
Hangzhou (Phase II)	107	113	2.11	13.7	0.009
Hangzhou (Phase III)	224	251	2.24	14.6	0.003
Hangzhou (Phase III (ADJ))	237	271	2.29	13.0	0.003

4 Conclusion

With the gradual increase in the number of subway lines and stations, the network density, clustering coefficient, average shortcut distance, and all centrality potential indicators of the overall subway network in Hangzhou gradually decrease. But in the phase III adjustment, the average shortcut distance, the betweenness centrality potential, closeness centrality potential, degree centrality potential have all rebounded significantly. This is closely related to the addition of the airport rail express line (which includes 15 stations) in the phase III adjustment. This express line greatly increases the overall cohesion of the original subway network and reduces the number of turnovers.

In the five planning stages, the Hangzhou subway network models constructed according to the Space L model all have a smaller clustering coefficient and a larger average shortcut distance. On the average shortcut distance, they have more characteristics as regular networks, but on the clustering coefficients, they have

more characteristics as random networks. Tests show that none of them has a small world characteristic, and neither has a scale-free characteristic.

The study of the complex network characteristic of the planned subway station network in Hangzhou will help to make decisions based on the TOD development advantages, potentials, and differences of different station areas, and provide a scientific basis for the formation of urban organic renewal strategies in the inventory optimization stage.

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