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TENDENCIES OF CHINESE SUBWAYS' SPATIAL GROWTH IN 2000-2020

Tendencje rozwoju przestrzennego chińskiego metra w latach 2000-2020

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Abstract: One of the main transportation problems of biggest modern cities is the excessively high load on ground transport, which is why the development of subway networks is of particular importance. This article analyzes the development of the spatial structure of subway networks in China. Currently China shows an intensive growth of existing networks and massive openings of new networks, which makes it the most suitable object for studying the evolution of subway networks. The methodology developed by K. Kansky and S. A. Tarkhov was used as the theoretical basis of this study. The study was conducted by analyzing the dynamics of the main quantitative and topomorphological indicators of subway networks during their passage through the stages of spatial evolution. The following indicators were used: the number of subways, the total length of the network, the number of cycles in the network, the number of topological layers and the number of cycles in each of them, the number of branching tiers, the area of topological layers and their share in the cyclic core of the network, the distribution of the length between the elements of the network structure, average cycle size, topological limit, cyclization index and circuity index. We identified the patterns for passing the stages of evolutionary development by the networks of Chinese subways; also, we found common features that define the "Chinese" type of subway, we identified a new subtype of networks.

Key words: subway networks, spatial structure, China, graph theory

1. Introduction

Currently economic growth in most countries leads to increase in urban population and it also causes traffic collapses and congestions in many big cities around the world. With the growth of the population in big cities, surface transportation networks can no longer satisfy all the transportation demands of the city, therefore, the construction of subway networks has become the most effective way of reducing the traffic load on the city's surface. The deterioration of the ecological situation in urbanized areas has also become one of the most important reasons for the development of subway networks. In many developed countries, subway networks have existed for a long time; these are mainly large cities and capitals: New York, Paris, London, Berlin, Hong Kong, Tokyo, Seoul, Moscow etc. In recent decades, there was a significant increase in the number of new subway systems in many countries, of which China stands out the most.

Two decades ago, the main modes of transportation for residents of Chinese cities were buses, bicycles and automobiles. The low share of the subways in the modal structure of transportation was largely due to the fact that at that time all subways in China were underdeveloped. The reason for this was mainly administrative factors: in the early 1990s. almost all the projects for the construction of subways that existed at that time were curtailed. They returned to development only in the early 2000s. As a result, over the next two decades, the situation changed dramatically, as it can be seen from the example of Beijing: in 2005, the share of the subway in total passenger traffic rose to 5.7%, in 2010 to 11.5%, and by 2015– up to 20.5% (Lu, Han, Lu,2016). In 2019, the total length of Chinese subway networks exceeded 5,200 km. Thus, in 20 years, China has gone from a country with 4 underdeveloped metro networks to the world's leader in terms of the number of subways, some of which are amongst the most developed in the world.

The main goal of this research is to identify the spatial patterns of the evolution for the Chinese subway. To complete it we've set the following tasks:

- to analyze the dynamics of quantitative indicators used to describe the growth of transport networks;
- to study the dynamics of topomorphometrical indicators reflecting the features of the development of networks' spatial structures;
- to reveal internal differences in the evolution of the spatial structures for various Chinese subway networks.

2. Literature review

This research was based on the papers of experts in the geography of transport and spatial self-organization of society: S.A. Tarkhov, V.A. Shuper, B.B. Rodoman, A.M. Yakshin, V.N. Bugromenko, I. Kohl, L. Lallane, W. Christaller, V. Garrison, K. Kansky, E. Taafe, R. Haggett, V. Vuchik.

One of the first geographers who researched the evolution of transport networks was I. Kohl. In 1841, using the Moscow road network as an example, he developed a transport-hierarchical model, thereby laying the foundation for all future approaches of researching the spatial structures of transport networks. Later L. Lallane revealed the dependence of the main geometric properties of the transport networks on the location of settlement networks and found definite patterns in the formation of railway networks in France, England and USA.

The first to apply graph theory to analyzing the spatial structures of the transport network was V. Garrison in 1960. He did this on the example of the road network of the southeastern part of the United States. In 1963, K. Kansky in his work suggested using 17 indices to describe the features of the spatial structure of the transport network, thus laying the foundations of network analysis in geographical science. Shortly after, E. Taafe and R. Morrill developed a stage model for the development of coastal transport networks. In 1969 P. Haggett and R.Chorley in their work «Network Analysis in Geography» analyzed all existing evolutionary models and defined general characteristic of growth for all types of transport networks.

In 1980-2000 interest in the application of graph theory for the analysis of transport networks has noticeably decreased, since the technical means at that time did not allow quick and detailed analysis of the processes of network evolution: each network required individual study, and mapping the network's structure at various stages of its evolution (which is necessary for its detailed study) took a considerable amount of time. And yet since the beginning of 2000 the development of GIS tools has greatly facilitated this process and this led to an increase in the number of works in the field of geographical network analysis.

Angeloudis and Fisk (2006) analyzed the largest metro networks at that time and identified two relative classes of complex networks that can be approximately determined using an evolutionary network with an associated exponential distribution, and also indicated that characteristics of high degree of connectivity at low maximum carrying capacity ensure the stability of such networks in case of random terrorist attacks. Jie and Shi (2007) investigated the possibility of subway networks to continue functioning normally in cases of environmental destruction, and they proposed an assessment model for the stability of the subway (based on the topology of the network and the distribution of passenger flows) and also developed 5 different variations of these models. Derrible and Kennedy (2009), based on the study of 33 subways, used various concepts of graph theory to describe three new network parameters: state (complexity of the network pattern), shape (connections of subway lines with surface area), structure (network properties). Gattuso and Miriello (2005) analyzed the subway networks using graph theory. Having studied the topological structures of 14 metro networks, they revealed the relationship between some structural parameters and the overall performance of the metro system. Hyun and Song (2015) studied the change in connectivity, reliability and accessibility of the Seoul subway network, identifying 4 main evolutionary stages.

Hong, Xu and Zhu (2017) studied the topological structure of the Nanjing subway network. In this work, based on the theory of the complex network, they developed topological models of the subway networks studying such indicators as the degree of distribution of nodes, the average length of the route, the diameter of the network and the degree of connectivity.

Roth et al.(2012) analyzed the evolution of the internal structure of the network on the basis of several major subway networks, focusing on the core-branch configuration. In this work, an attempt was made to parameterize the geometric configurations of the networks of various subways. The authors conclude that the average degree of a node (station) within the core of the network is 2.5, the number of branches is approximately equal to the square root of the number of stations, and the average length of a branch is twice the radius of the core. At the same time, the authors consider the core of the network as a single monolithic entity and do not attempt to identify various elements within the core.

Wu, Dong, Tse et al.(2018) analyzed the structure of subway networks through the prism of complex networks. They studied the various characteristics of the operation of subway networks, conducted an analysis of the stability of the network to impacts of various externalities. Subway networks of New York, Beijing, London, Paris, Hong Kong, Tokyo were analyzed. New York City subway network has been proven to be the most topologically efficient, while the Tokyo and Hong Kong networks– the most resilient.

In our previous research (Panov, 2020) we made a comparative analysis of spatial structures' evolution for some of world's biggest subway networks: Shanghai, Beijing, Tokyo, Seoul, London, and New York. We found out that while subway networks of New York and Tokyo had slightly more complex spatial structure, networks of Beijing and Shanghai had better connectivity.

3. Models and methods

In this research to study the evolution of the spatial structures of Chinese subway networks we use the method developed by S.A. Tarkhov (2005) based on the research of K. Kansky (1963). It includes a detailed analysis of the internal structure of the "core" of the transport network, identifying the stages of its development.

To analyze the evolution of China's subway networks, we use graph theory, transforming the transport network into a graph, where subway stations become vertices, and the routes between them become edges.

The main structural components of the transport network transformed into a graph are a cycle– a closed loop of roads (paths) in the network, i.e. a figure formed by several transport lines in the form of a closed cell– the basic spatial element of the transformed network (Fig.1)

Fig. 1. Left: cycle, formed by 3 edges and 3 vertices; Right– single edge with 2 vertices

Source: own elaboration of the author

Cycles in transport networks are most often grouped into compact clusters which we call cyclic cores. It is essentially the same cores which are discussed in other researches focusing on core-branch structure of subway networks. (Roth et al,2012). For further analysis of the core we use a concept of topological layer (Tarkhov, 2005). Topological layer is a closed annular band of cycles (similar to tree ring on the cut of a tree trunk)– such that it includes cycles that have at least one common vertex or edge with its outer boundary. In the beginning of its growth most of the cores has only one layer, but later that numbers increase (usually up to 3-4 at most for most developed subway networks).

On the Figure 2 you can see an example of a subway (Bejing's subway at 2016) with cyclic core with 3 topological layers.

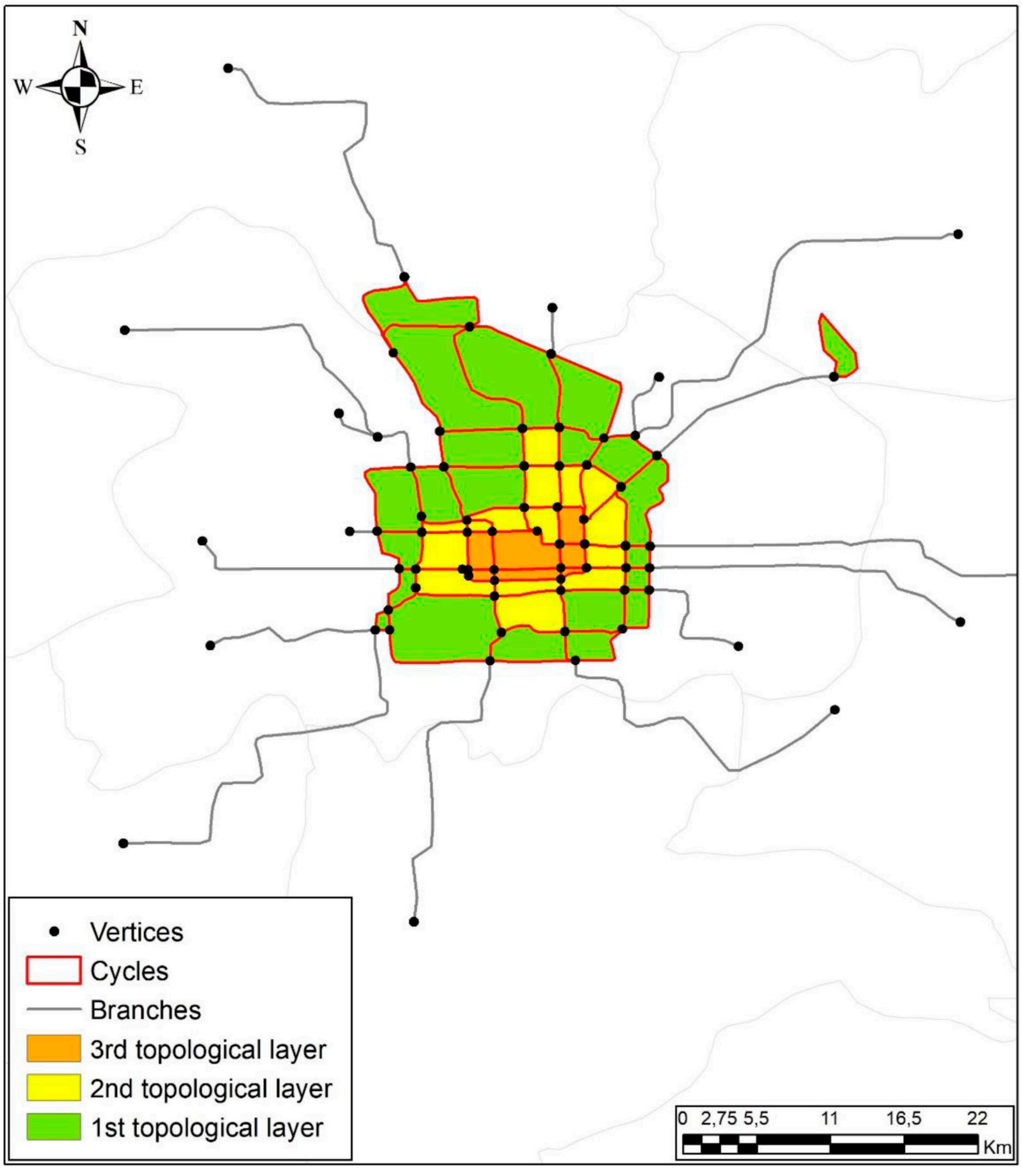


Fig. 2. Spatial structure of Beijing's subway network at 2016 (3-rd class network)

Source: own elaboration of the author

This research of the evolution of Chinese subway networks was carried out by analyzing the dynamics of the following indicators over the past 20 years: the total number of networks (subway systems), the length of their lines, the number of cycles, the share of branches and the cyclic core in the total length of the network, cyclicity indices, intensity of cyclisation, the number of topological layers and their internal structure, the topological limit.

4. Results of the research

At the beginning of 2020 there were 38 subway networks in China: Wenzhou, Guangzhou, Guiyang, Dalian, Dongguan, Kunming, Lanzhou, Nanjing, Nanning, Nanchang, Ningbo, Beijing, Xian, Suzhou, Xuzhou, Xiamen, Tianjin, Urumqi, Wuxi, Wuhan, Foshan, Fuzhou, Hangzhou, Harbin, Hohhot, Hefei, Jinan, Qingdao, Changzhou, Changchun, Changsha, Chengdu, Zhenzhou, Chongqing, Shanghai, Shijiazhuang, Shenzhen, Shenyang. Back in 2000 subways operated only in 4 cities– Beijing, Shanghai, Guangzhou and Tianjin, but starting from 2005 the number of subways began to increase as it's shown at figure 3.

As it can be seen in the Fig.3, period from 2010 to 2017 was the most intensive in terms of the number of newly opened subway systems, afterwards the growth rate decreased. In 2017, the Chinese government decided to reduce the population requirement for cities planning to build new subway systems from 3 to 1.5 million inhabitants. In this regard, more than 43 relatively small cities have received permission to

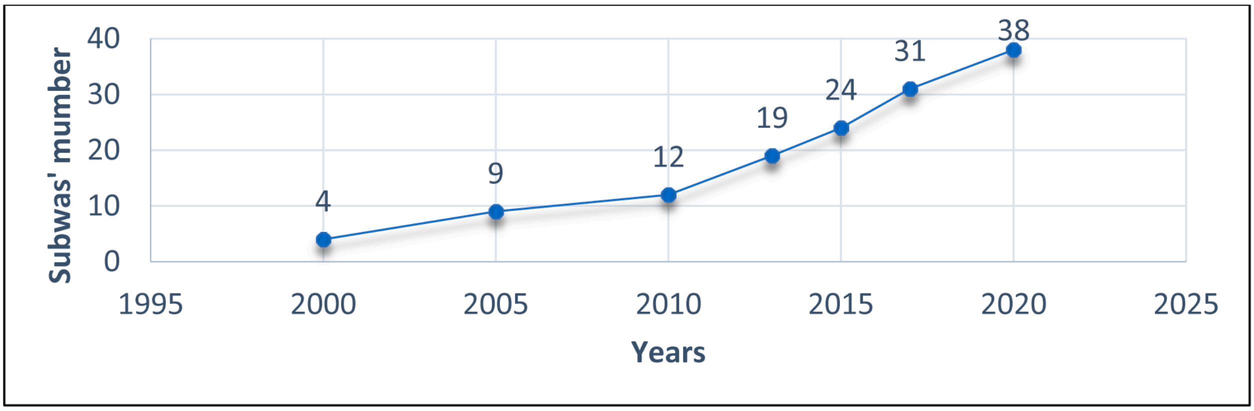


Fig. 3. Subway networks in China (2000-2020).

Source: Kai Lu, Baoming Han, Fang Lu. Urban Rail Transit in China: Progress Report and Analysis (2008–2015). Urban Rail Transit, 2016, 2 ,93–105

develop subway network projects, which means that the growth rate of the number of subway systems in China will remain at the same level in the coming years.

One of the most commonly used indicators describing the size of transport networks is the total length of the network. But by itself, this indicator is not suitable for analyzing the spatial structure of the network, since it does not reflect the features of the internal structure of the network, but only gives a general idea of the size of the network. Therefore, we will analyze the dynamics of this indicator together with the dynamics of the total number of cycles in all subway networks in China. The number of cycles is one of the basic indicators characterizing the structure of the network. Cycles make network's structure more stable: in case of tree-shaped network which consists only of branches disruption on branch will stop the traffic flow, but in cyclic networks it's possible to find another route.

The growth and evolution of the subway network consist of two processes – cyclization (increase in the number of cycles in the cyclic core) and branching (growth of branches). In our case cyclization can occur both through the creation of absolutely new cycles and through the fragmentation of existing ones. When cycles split, the increase in the total length of the network will be less than in case of creation of totally new ones. In the Fig.4 we can see the alternation of these processes in Chinese subway networks, although not as clearly as it could have been seen in the example of one network. The period from 2008 to 2016 is characterized by the dominance of cyclization and the period from 2016 to 2020 is characterized by domination of branching. The reason for the decrease in the rate of cyclization is the slowdown in the growth of the number of cycles in the most developed subway networks of Beijing and Shanghai and the continuation of growth of the number of tree (without cycles)

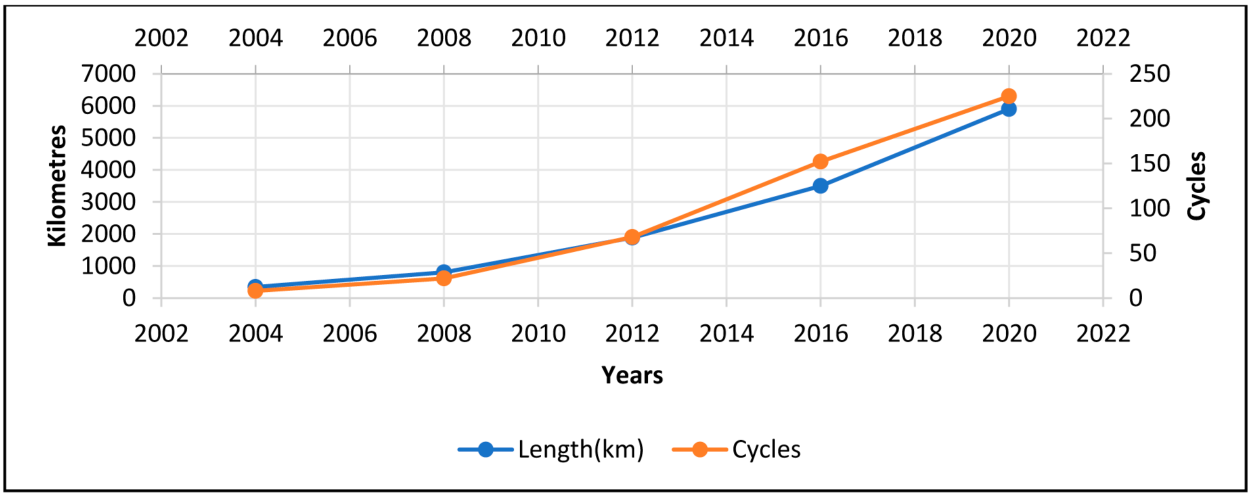


Fig. 4. Dynamics of total length and number of cycles in Chinese subway networks (2004-2020).

Source: own elaboration of the author based on OSM data

networks. Figure 5 shows the dynamics of growth of the length and number of cycles in the two largest subway networks– Beijing and Shanghai.

Among the cyclic networks of Chinese subways two the most developed networks of Beijing and Shanghai each have three topological layers and they

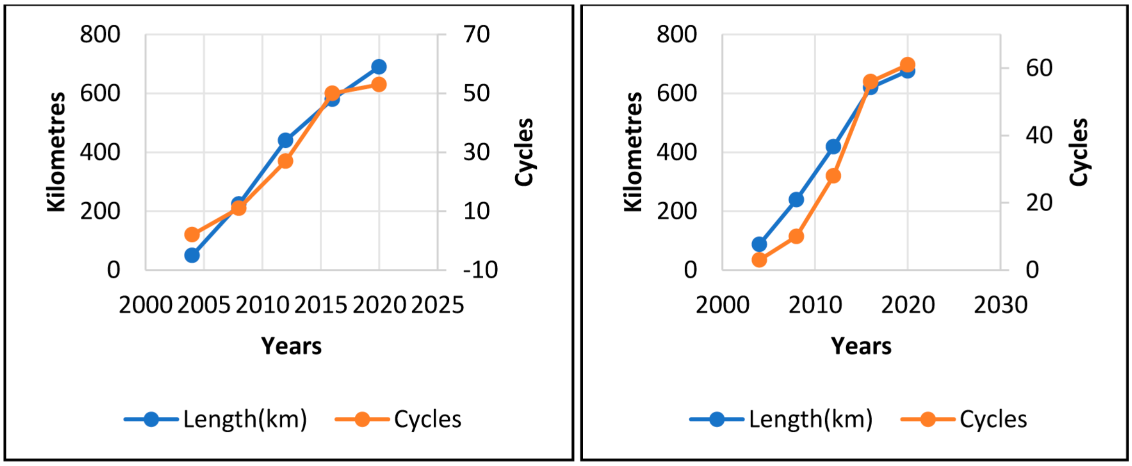


Fig. 5. Dynamics of total length and number of cycles in subway networks of Beijing (left) and Shanghai (right) (2004-2020).

Source: own elaboration of the author based on OSM data

These figures clearly show a change in the general trend for both networks in 2016: the number of generated cycles began to decrease, and it is more defined in Beijing than in Shanghai. The reason for this is the difference in the distribution of the length of the network between various elements of its spatial structure: in the Beijing subway network, the cyclic core concentrates 55-60% of total length and in Shanghai it's 35-40%.

While analyzing the spatial structure of networks of subway lines, we divide all networks into 2 main classes: cyclic networks and tree networks. Tree networks consist exclusively of branches and do not have cycles in their composition. The degree of complexity of their development can be estimated by the number of tiers of branching. They can continue to grow as tree networks, or move into a more complex class of cyclic networks. In general, tree subway networks are not characterized by a high number of branching tiers; almost all of them very early move into the class of cyclic networks. Cyclic networks have at least one cycle in their composition, and their development consists in alternating cycle formation by creating or splitting cycles. This leads to an increase in the number of topological layers in the cyclic core and the number of topological layers determines the class of the network. The cyclic network of the 1st class has 1 topological layer, the 2nd class network has 2, etc. This research mostly concentrates on analyzing cyclic networks as the spatial structure of tree networks is developed insufficiently.

are followed by the networks of Shenzhen, Guangzhou and Wuhan – all of them have two topological layers and are currently on the verge of moving to the next class. The networks of Chongqing, Chengdu and Tianjin that follow them are left far behind. Most of the subways with one topological layer have just recently moved to the class of cyclic networks, and among these networks– the Nanjing network is currently closest to the transition to the second class – it can be seen from Table 1.

Onwards we will only consider networks with two and three topological layers, since networks with one topological layer do not yet have a sufficiently developed spatial structure. There are 8 networks with 2-3 layers in total.

The network growth rate is estimated by calculating the cyclization intensity index. It is calculated as the ratio of the number of cycles in the network to the number of years that have passed since the formation of the first cycle in the network until the network reaches the maximum level of development. This indicator reflects the overall growth rate and the frequency of changes in the spatial structure of the network. For Chinese subways, it ranges from 2 (Tianjin) to 4 (Beijing and Shanghai); the exception is Shenzhen (7) – in this network, active cyclization began only in the early 2010s.

The next indicator used by us to analyze the spatial structure of the network is the distribution of the area of the cyclic core between the topological layers. It displays the spatial features of the internal structure of the network.

Tab. 1. Number of cycles and topological layers in Chinese subway networks (2020).

City	Number of layers	Cycles	City	Number of layers	Cycles
Shanghai	3	61	Xian	1	3
Beijing	3	53	Changsha	1	3
Shenzhen	2	28	Suzhou	1	2
Guangzhou	2	22	Hangzhou	1	2
Wuhan	2	21	Nanchang	1	1
Chongqing	2	13	Qingdao	1	1
Chengdu	2	11	Hefei	1	1
Tianjin	2	9	Nanning	1	1
Nanjing	1	6	Ningbo	1	1
Changchun	1	4	Shenyang	1	1
Zhengzhou	1	4			

Source: Open Street Maps

The share of the area of the third topological layer does not exceed 10% (Fig,6), thus the 10% boundary is a limit and a goal for the class 3 Chinese networks' structures. The shares of the second and third topological layers in the Beijing network are higher than in the Shanghai network; this means that the Beijing network as a whole is more balanced. Among the networks of the 2nd class, 2 groups can be clearly distinguished: the share of the 2nd topological layer in the networks of Shenzhen, Guangzhou and Wuhan is noticeably higher than in the networks of Chongqing, Chengdu and Tianjin. In the networks of Beijing and Shanghai at the time of their transition to the 3rd class, a similar distribution of the area of the cyclic core was also observed.

Thus, the more cycles in the topological layer are and the smaller their area is, the more complex is its structure and the higher is its resistance to various violations of structural integrity, and less likely it is for this layer to form new cycles by splitting existing ones. Further cycling in such a layer is possible due to the transition of cycles from other layer to it or due to creation of totally new ones.

Fig.7 shows that although the distribution of layers' area in the Beijing subway network indicates a greater stability of its structure as a whole, the distribution and average area of cycles show greater internal stability in the topological layers of the Shanghai subway network.

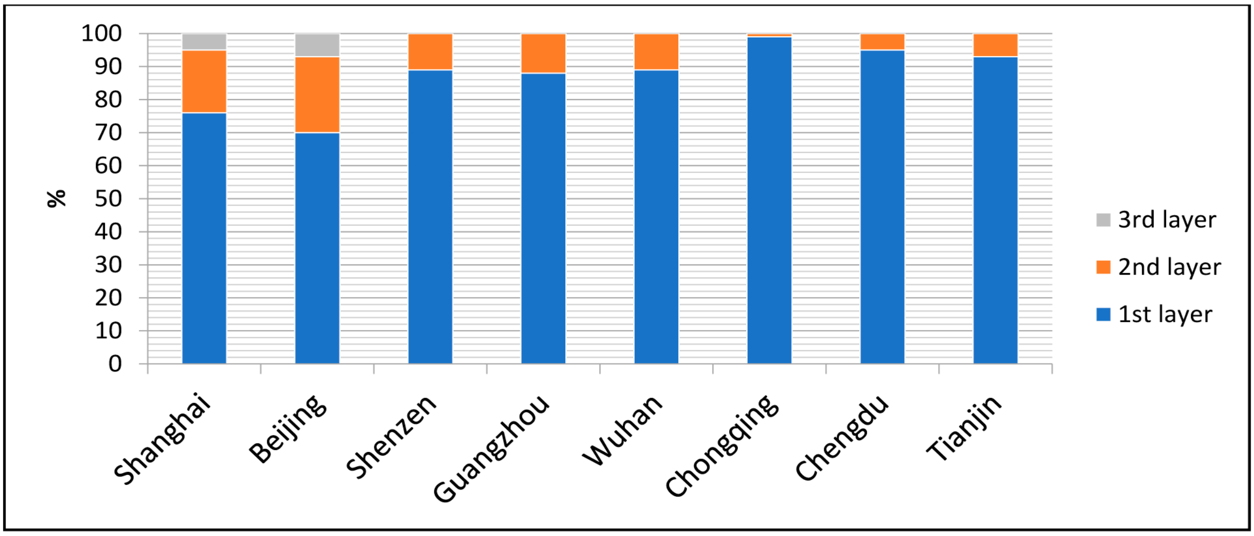
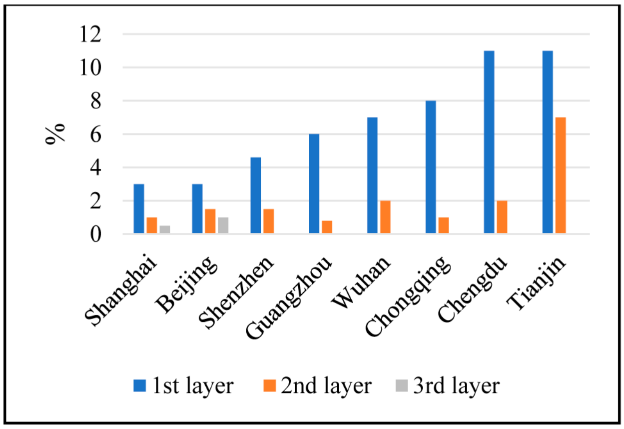


Fig. 6. Distribution of layers inside the cyclic core, %,2020.

Source: own elaboration of the author based on OSM data



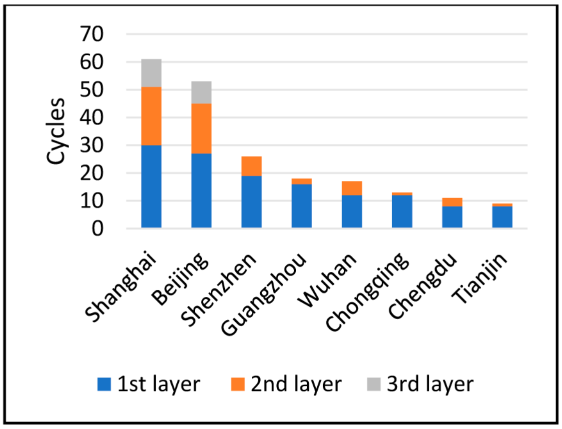


Fig. 7. Ratio of the average area of cycle to the total area of cyclic core, % (left), distribution of cycles in topological layers (right). 2020.

Source: own elaboration of the author based on OSM data

Such thing happens mainly because of a larger number of cycles, although in general the value of the average size of cycles are approximately at the same level. The average size of cycles in the layers of the Shenzhen and Guangzhou networks has already reached the level of the Beijing and Shanghai networks. Therefore, we assume that the soon-to-come formation of the third topological layer in them will bring them to a level similar to the networks of Beijing and Shanghai. The remaining four networks of Wuhan, Chongqing, Chengdu and Tianjin lag far behind the rest in all respects.

Any network must accumulate a certain number of cycles before moving to the next level of topological complexity. We called this number the topological limit of the network. Table 2 shows the values of this limit for the networks we studied.

Table 2 shows that the limit for the transition from the 1st class to the 2nd class is "floating", it does not have strict boundaries and ranges from 4 to 10. The limit of the 2nd layer is much more defined and it is approximately 28 cycles. It is worth noting that such a low transition limit to the 3rd class of topological complexity is a distinctive feature of Chinese subways; for comparison, the topological limit of the networks of New York, London, Seoul, Tokyo at the time of the formation of the 3rd topological layer was 36-40 cycles (Panov,2020). In general, this indicates an increased stability of the network structure, since otherwise a relatively small number of cycles would not be sufficient to form a new tier.

The distribution of the network length between the cyclic core and branches is quite an important factor affecting the overall connectivity of the network (Fig. 8).

Tab. 2. Topological limit for Chinese subway networks (2020).

City	1st class	2nd class
Shanghai	10	28
Beijing	9	27
Shenzhen	9	
Guangzhou	7	
Wuhan	8	
Chongqing	4	
Chengdu	3	
Tianjin	4	

Source: own elaboration of the author based on OSM data

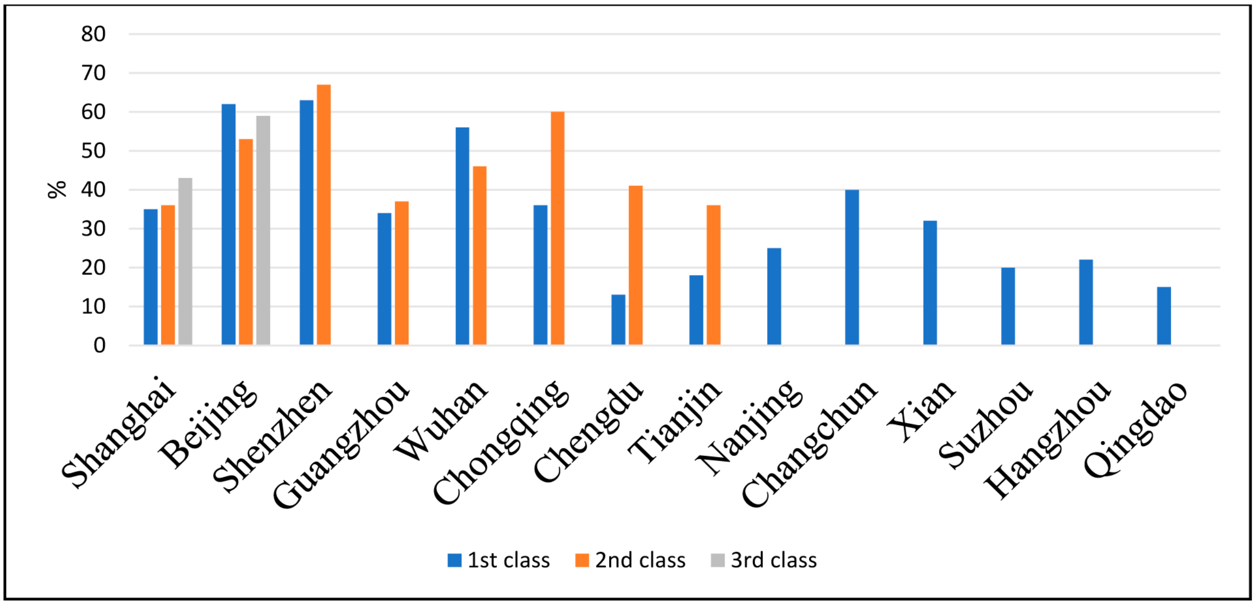


Fig. 8 The proportion of the cyclical core in the total length of the Chinese subway networks.

Source: own elaboration of the author based on OSM data

As it can be seen in Fig.8 in most cases length distribution structure has a shift towards branches. In networks with a low degree of cyclicity, it can be explained by a small number of cycles and their small size, as well as a high degree of development of the tree part of the network. With the further development of the network, in most cases the situation gradually changes– the proportion of the cyclic core increases. The only networks where the cyclic core has dominated since its creation are Beijing and Shenzhen metro networks.

To characterize the network as a whole, we used the cyclicity index α. It is calculated by the formula α = u/2*v– 5, where u is the number of cycles in the core, v is the number of vertices. This index shows the ratio of the existing number of cycles in the network to their maximum possible number for a given number of vertices, thereby reflecting the degree to which the network realizes its potential in cyclization, which is an extremely important indicator for us.

Chinese subways are generally characterized by rather high values of the cyclicity index even at the early stages of network development (Table 3)

Most often with the increase in the complexity of the network structure, the index values also increase, reaching a maximum at the time of the formation of the 3rd topological layer. At the same time in the networks of Beijing and Shenzhen the growth of the values of this index was much faster than in the others. This happened because the initial dominance of the cyclic core in the overall structure of the network.

Tab. 3. Dynamics of alpha-index in Chinese subway networks.

City	1st class	2nd class	3rd class
Shanghai	0,2	0,25	0,27
Beijing	0,3	0,3	0,35
Shenzhen	0,25	0,35	
Guangzhou	0,17	0,2	
Wuhan	0,2	0,2	
Chongqing	0,26	0,22	
Chengdu	0,1	0,22	
Tianjin	0,15	0,2	

Source: own elaboration of the author based on OSM data

5. Conclusion

Despite the fact that there has been an increase on the researches on subway networks in the recent years, sometimes it is difficult to compare the results of the researches because of differences in methods. Most of the other researches concentrate either on one subway or on worldwide selection of largest subway systems. So, one of the important goals of our research was to show that an explosive growth of number of subways in China made it possible to carry out pure country-wide research (at least in China).

After analyzing the dynamics of changes in a number of quantitative and topomorphometric characteristics of the Chinese subway networks and their spatial structures, we came to the following conclusions:

1) In the dynamics of the total length of all subway networks in China, fluctuations appear, depending on the alternation of cyclization and branching during the evolution of the network. At the same time, cyclization occurs due to the continued growth of cyclically developed networks, and dendritic formation occurs due to the emergence of new tree-like networks.
2) The spatial structures of China's subway networks have similar characteristics and distinct features: similar distribution of areas of topological layers and sizes of cycles; "floating" topological limit of the 1st class and a well-defined limit of the 2nd class; a small number of cycles in comparison with the largest networks from other countries, while having a high level of cyclic development and connectivity of the network.
   All these features allow us to highlight a special "Chinese" type of metro networks.
3) Despite the fact that most of China's subways can easily be attributed to one type, the spatial structure of the networks of Beijing and Shenzhen makes us classify them as a separate subtype with an increased role of the cyclic core in the process of network evolution– the "hyper-core" type of networks.

At present, the Chinese subway networks are the most suitable object for studying the evolution of the spatial structure of the subway networks, since they have a high growth rate along with the ongoing construction and commissioning of new networks and lines. In a few years, a similar study will reveal even more pronounced features of the Chinese type of subways.

References

Angeloudis P, Fisk.D, 2006, Large subway systems as complex networks // Physica A, Vol. 367. № 3, 553–558.

Derrible S., Kennedy C., 2009, A network analysis of subway systems in the world using updated graph theory // Transportation Res. Rec., V. 2112. № 1, 17–25.

Gattuso D., Miriello E., 2005, Compared Analysis of Metro Networks Supported by Graph Theory // Networks and Spatial Economics, V. 5. № 4, 395–414.

Guo J., Sun M., Wang T, Lu L., 2015, Transportation Development and Congestion Mitigation. Measures of Beijing, China. Mitigation and Adaptation Strategies for Global Change, 20, 651–63.

Haggett P., Chorley R.J., 1969, Network Analysis in Geography. London: Edward Arnold,. 348 p.

Hong C., Xu T., Zhu J., 2017, A comparative study of the topological structure of Nanjing metro network based on whole perspective // Ind. Eng J., Vol. 20. № 5, 51-57.

Hyun K., Song Y., 2015, Examining Accessibility and Reliability in the Evolution of Subway Systems // Journal of Public Transportation, Vol. 18. №. 3, 89-106.

Jie G., Shi Q., 2007, Definition and evaluation modeling of metro network invulnerability // Journal of China Railway Society, Vol.29. №. 3, 26-36.

Lu K., Han B., Lu F., 2016, Urban Rail Transit in China: Progress Report and Analysis (2008–2015). Urban Rail Transit, 2, 93–105.

Kansky K.J., 1963, Structure of transportation networks: relationships between network geometry and regional characteristics. Chicago: Chicago Univ., Department of geography, Research paper, 155 p.

Lam T.N., Schuler H.J., 1981, Public Transit Connectivity. V. 1. Report DMT-084. Irvine: Univ. of California, 51 p.

Lam T.N., Schuler H.J., 1982, Connectivity Index for System wide Transit Route and Schedule Performance // Transportation Res. Rec. 854. TRB. National Res. Council. Washington, D.C., 17–23.

Musso A., Vuchic V.R., 1988, Characteristics of Metro Networks and Methodology for Their Evaluation // Transportation Res. Rec. V. 1162. TRB. National Res. Council. Washington, D.C., 22–33.

Panov R.D., 2020, Evolyutsiya prostranstvennoi struktury krupmeishih metropolitenov mira [Evolution of Spatial Structure of the World's Biggest Subway Networks], Moscow, Izvestiya Rossiiskoi Akademii Nauk. Seriya Geograficheskaya. Vol.1, 20-26.

Roth C.,Kang M.C., Batty M., Barthelemy M., 2012, A long-time limit for world subway networks // Journal of Royal Society Interface, Vol. 9. № 9, 2540–2550.

Taaffe E.J., 1996, Geography of Transportation. Prentice-Hall, Upper Saddle River, N.J., 422 p.

Tarkhov S.A., 2005, Evolyutsionnaya morfologiya transportnykh setei [Evolutional Morphology of Transport Networks]. Smolensk, Moscow: Universum Publ., 384 p. (in Russian)

Wu X., Dong H. Tse C.H. et al., 2018, Analysis of metro network performance from a complex network perspective // Physica.A. Vol.492, 553-563.