第12卷 第5期
2012年10月
交通运输工程学报
Journal of Traffic and Transportation Engineering
Vol. 12 No. 5
Oct. 2012

文章编号:1671-1637(2012)05-0064-08

基于复杂网络的城市路网结构分析方法

张卫华,杨 博,陈俊杰
(合肥工业大学 交通运输工程学院,安徽 合肥 230009)

摘 要:在城市道路网络的基础上,探讨了应用复杂网络理论的可行性和有效性。运用Dijkstra最短路径算法和Space L方法建立初始拓扑网络,并建立了节点度、边度和节点路阻的特性指标模型。在反映路网功能真实性的前提下,优化了拓扑网络,并以某市中心城区道路交通数据为例进行实例分析。分析结果表明:在初始网络中,节点度数的均值为2.850 0,标准差为0.670 8;节点路阻的平均值为84.680 0 s,标准差为11.768 8 s;在优化网络中,节点度数的均值为38.750 0,标准差为24.683 0,节点路阻的平均值为91.780 0 s,标准差为18.862 8 s;东西向边的平均度数为42.00,南北向边的平均度数为29.86,内部边的平均度数为55.00,外部边的平均度数为28.33。在优化网络中,当度数较大的节点在路网中失稳时,在非拥挤状态下,最短路径路阻增大,而在拥挤状态下,网络会瘫痪。度数较大的节点与真实路网中交叉口重要程度相符,能够体现交叉口重要程度的差异性。

关键词:交通规划;城市路网;最短路径;复杂网络;Dijkstra算法;Space L方法
中图分类号:U491.13 **文献标志码**:A

Analysis method of urban road network structure based on complex network

ZHANG Wei-hua, YANG Bo, CHEN Jun-jie
(School of Transportation Engineering, Hefei University of Technology, Hefei 230009, Anhui, China)

Abstract: Based on urban road network, the feasibility and effectiveness of complex network theory application were analyzed. By using Dijkstra shortest path algorithm and Space L method, the initial topology network was built, and the characteristic index models of the degree of node, the degree of edge and the road impedance of node were set up. Under the premise of reflecting the reality of road network function, the initial topology network was optimized, and empirical analysis was carried out by using road traffic data in a central urban area. Analysis result shows that in the initial topology network, the average node degree is 2.850 0 and the standard deviation of node degree is 0.670 8. The average road impedance of node is 84.680 0 s and the standard deviation is 11.768 8 s. While in the optimal topology network, the average node degree is 38.750 0 and the standard deviation of node degree is 24.683 0. The average road impedance of nodes is 91.780 0 s and the standard deviation is 18.862 8 s. The average degree of east-west road section is 42.00, the average degree of north-south road section is 29.86, the average degree of internal section is 55.00, and the average degree of external road section is 28.33. In the optimal topology network, when the node with large degree is not stable, the road impedance of shortest path will increase in non-crowded state, and the road network will be paralyzed in crowded state.

Receipt Date: 2012-05-22
Research Projects: National Natural Science Foundation of China(51178158); Special Fund for Basic Scientific Research of Ceatral Colleges (2010HGZY0010)
Author Resume: ZHANG Wei-hua(1967-), Male, Anqing, Anhui, Professor of Hefei University of Technology, PhD, Research on Urban Traffic Planning, +86-551-2901960, hfutits@163.com.

The node with higher degree is accord with the importance degree of intersection in real road network, and the difference of importance degree for intersection can be more reflected. 4 tabs, 6 figs, 15 refs.

Key words: traffic engineering; urban road network; shortest path; complex network; Dijkstra algorithm; Space L method

0 Introduction

The urbanization level in China is improved constantly in recent years. By the end of 2011, there are 14 cities which have more than 2 million people. The number of motor vehicle population has reached 223 million, and vehicle population is more than 100 million. Meanwhile, there are 14 cities which have more than 1 million vehicles. The rapid development of motor vehicle will cause the great burden of urban road network. In the process of urban development, road network has become the foundation in the development of urban traffic. Reasonable road network structure can not only affect the land expansion, but also affect the remission of traffic pressure. With the accelerating process of urbanization and the rapid growth of motor vehicle amount, reasonable road network structure is especially important for the stable development of urban economy as well as the safety of resident travel.

Mine et al most early put out the original network structure characteristic, which was network connectivity reliability[1]. Due to the defects of connectivity reliability in describing the real-time dynamic change of traffic network, CHEN et al put forward the travel time reliability and road network capacity reliability in the respect of traveler system[2-3]. The above three kinds of network characteristics are firstly proposed, and then researches on road network structure have been increasing gradually. The complex network theory is used to research complex system, the development in the first two stages are marked by seven bridge problem in 1736 and random diagram theory in 1959. In the third stage, Watts et al introduced the concepts of small-world network and scale-free network[4-6]. Then, the applications of complex network in different fields are attentioned gradually, and there are many studies on urban road network structure now. Based on complex network theory, Jiang et al quantified the importance degree of certain urban road network by establishing characteristic indexes, and studied road network structure by using some practical examples[7]. Porta et al made a contrastive analysis on six original topology network and dual topology network with different road network structures, and found that neither power-law distribution nor small-world characteristic could be reflected in the city with one square mile[8]. Lammer et al analyzed topology characteristics of road networks with over 20 large cities in German, found that traffic flow distributions had power-law characteristics, and illustrated the road grade characteristics[9]. Latora et al put forward the concept of road network efficiency to measure road network structure, and found that it was applicable for global and local small-world networks[10]. Based on the construction of road network in Italy, Andrea et al analyzed the basic characteristics of road network and the relationship between road network structure and traffic volume and provided a theoretical basis for the optimal control strategy of road network structure[11]. Gao et al proposed the application of complex network in traffic field from several angles, and conducted the corresponding researches[12-13]. Jiang constructed urban topology road networks by using different construction methods, and analyzed the road networks with different characteristic indexes[14]. However, it is obvious that topology network aimed by the existing characteristic indexes is too large, which is composed of hundreds or even thousands of nodes and edges, and it can not truly reflect the role and characteristics of road network in urban traffic.

Now, there is not enough existing theory to research the characteristics of road network structure in the real traffic environment. Based on a mass of researches of complex network, a network topology conversion method is constructed to reflect the function of road network structure in urban traffic. Meanwhile, the structure characteristics of road network are analyzed and summarized by constructing the corresponding indexes.

1 Condition of network establishment

In order to reflect the real traffic situation of urban road, the initial topology network needs to be established firstly. Then the path with the minimum road impedance among the nodes in the initial topology network is obtained by calculating the road impedancs of all road sections. Multiple paths are acquired by Space L method[15], and the optimal topology network is established.

1.1 Path selection

Path selection could be regarded as a traffic assignment problem in four-stage method. However, in the past methods, the traffic assignment was the assignment result of traffic occurence amount and traffic attraction amount among all traffic zones. In this paper, the traffic assignment of origin-destination is transformed into the traffic assignment among the nodes, and the shortest path allocation method is used. Assuming that the shortest path is selected to travel. Generally, the path selection relies on the subjective judgments of travelers. But major areas in many cities are in a non-saturation at non-peak periods, except the central areas in some big cities. The selection behavior of shortest path is not influenced by the traffic flow among other existing nodes in road network. By considering the influence of traffic flow on the impedance of road section, traffic flow should be considered.

1.2 Definition of road impedance

Generalized traffic impedance in this paper is the resistance role on travel caused by four factors, such as human, vehicle, road and environment. Narrow traffic impedance is travel time, which can be quantified by mathematical method. So, BPR impedance function is used.

1.3 Establishment method

There are mainly two topology methods about the analysis of urban road network[14-15]. In original topology network, the road section is taken as edge and intersection is taken as node. In dual topology network, the road section code or road section name is taken as node, the same road section name can be taken as one node, and the intersection becomes a connecting line between two nodes. Original topology method is selected to establish the initial topology network of urban road network. Firstly, establishing the initial topology network in actual urban road network structure, which is relatively simple and easy to operate. Secondly, the road sections with the same name or same code in dual topology network are taken as a node, which will be subjective and random. So it can not reflect road network structure objectively and intuitively. Meanwhile, the smaller the size of road network is, the greater influence of the subjective randomness of name or code on the formation of topology network will be. Thirdly, selecting original topology newtork is beneficial to the calculation process of road impedance and characteristic indexes.

1.4 Conversion method of initial topology network

The minimum road impedance from one node to the others is calculated according to Dijkstra shortest path algorithm. The initial topology network is a directed network, and there are several paths among those nodes. The set and sequence of nodes are obtained. In the optimal network, the node is the one in initial topology network, and the connecting line is the path with the minimum road impedance.

Through the above steps, the optimal topology network is obtained by abstract conversion, and the smaller topology networks are converted into a medium or large topology network. At last, the characteristic indexes are used to analyze the structure of road network.

2 Model establishment

The prerequisite of model establishment is that there are n nodes and m edges in road network, meanwhile, in the case of no real-time road traffic induced information, vehicle will select the path with the minimum road impedance.

Based on the physical structure of urban road network, length d_{ij} from node i to node j ($i \neq j$), capacity c_{ij} and traffic flow q_{ij} are divided into standard cars, and are acquired by investigating the length, capacity and traffic flow of road sections. d_{ij}, c_{ij} and q_{ij} are taken as initial input data, and a directed graph which is taken as initial topology network is built by regarding intersection and section as node and edge respectively. Based on the road data of initial topology network, the impedance t_{qij} of road section from node i to node j is calculated. The BPR impedance function is used, which is

$$t_{qij} = t_{ij0}[1 + \alpha(q_{ij}/c_{ij})^{\beta}] \tag{1}$$

where t_{ij0} is the travel time of free flow form node i to node j; c_{ij} is the actual capacity from node i to node j; α, β are regression coefficients, α is 0.15 and β is 4.

After acquiring the road impedances among nodes, the minimum road impedance and the sequence are acquired by using Dijkstra shortest path algorithm. Dijkstra algorithm is a typical single-source shortest path algorithm, and is used to calculate the shortest path from a node to the other nodes. Nowadays, the steps of the algorithm have been relatively mature. Finally, the path with the minimum impedance and the sequence of the paths are acquired. There are n nodes in the initial topology network, and the initial topology network is a directed graph. The model is improved by using the existing complex network theory. The three characteristic indexes such as the degree of node, the road impedance of node and the degree of edge are calculated and are used to analyze the structure of road network. The degree of node in this paper is the outdegree of node in the optimal network, and the starting points of paths are not considered when calculating the degree of network. Although the path has only a starting point and an end point, the degree of a node will be one at least. So removing the degree of starting point can reflect the importance degree of node actually. There is

$$k_i = \sum_{f=1}^{N} \sigma_{if} - (n-1) \tag{2}$$

where k_i is the degree of node i ($i = 1, 2, \cdots, n$); N is the total number of paths with the minimum road impedances among different nodes, and the total number is $n(n-1)$; σ_{if} is 0-1 decision variable, if the shortest path f goes through node i, σ_{if} is 1, otherwise σ_{if} is 0.

The road impedance of node in this paper is the average value of minimum road impedances from one node to the others. The road impedance from one node to another node is calculated by Dijkstra algorithm. There is

$$\bar{l}_i = \frac{\sum_{j=1}^{n} l_{ij}}{n} \tag{3}$$

where $\bar{l}_i$ is the average value of minimum road impedance from node i to the others; l_{ij} is the road impedance of the shortest path from node i to node j.

The degree of edge in this paper is the total number of path with the minimum road impedance which goes through edge s. There is

$$k_s = \sum_{f=1}^{N} \sigma_{sf} \tag{4}$$

where k_s is the degree of edge s ($s = 1, 2, \cdots, m$); σ_{sf} is 0-1 decision variable, if the path with the minimum road impedance f goes through edge s, σ_{sf} is 1, otherwise σ_{sf} is 0.

3 Calculation result analysis

Combined with the improvement planning data of road traffic in a central urban area, the urban road network structure is analyzed based on the initial topology network. The initial topology network is shown in Fig. 1, ① is intersection 1, 1(22.5) is that the road impedance of section 1 is 22.5 s. The edge with an arrow is one-way traffic, and the edge without an arrow is two-way traffic.

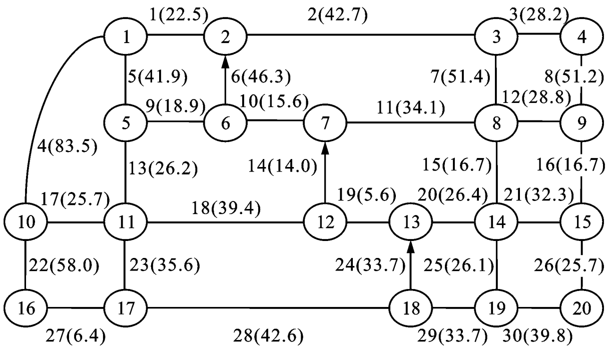

Fig. 1 Initial topology network

The initial network topology is built. There are 20 nodes and 30 sections, 3 one-way traffic sections and 3 nodes with steering restriction measure. Through invesgating the traffic data, the impedances of various road sections are calculated . The minimum road impedances among the first ten nodes are shown in Tab. 1. The row nodes are starting points, and the column nodes are finishing points. The node sequences among the first ten nodes are shown in Tab. 2. Through programming, the $n(n-1)$ paths are obtained, and the degrees of nodes, the degrees of edges and the road impedances of nodes are calculated by Eqs. (1)-(4). The road impedances of nodes in the optimal topology network are shown in Fig. 2. The average lengths of edges by the conventional method are shown in Fig. 3. The degrees of nodes are shown in Fig. 4. Curve 1 is obtained by applying the method in this paper, while curve 2 is obtained by applying the conventional method.

Tab. 1 Minimum road impedances s

Node	1	2	3	4	5	6	7	8	9	10
1	0.0	22.5	65.2	93.4	41.9	60.8	76.4	110.5	139.3	83.5
2	22.5	0.0	42.7	70.9	64.4	46.3	61.9	94.1	122.1	106.0
3	65.2	42.7	0.0	28.2	107.1	89.0	85.5	51.4	79.4	148.7
4	93.4	70.9	28.2	0.0	135.3	117.2	113.7	79.6	51.2	176.9
5	41.9	64.4	107.1	135.3	0.0	18.9	34.5	68.6	97.4	51.9
6	60.8	83.3	101.1	129.3	18.9	0.0	15.6	49.7	78.5	70.8
7	76.4	98.9	85.5	113.7	34.5	15.6	0.0	34.1	62.9	79.1
8	110.5	94.1	51.4	79.6	68.6	49.7	34.1	0.0	28.8	113.2
9	139.3	122.1	79.4	51.2	97.4	78.5	62.9	28.8	0.0	142.0
10	83.5	106.0	140.8	176.9	78.9	97.8	113.4	40.8	169.6	0.0

Tab. 2 Node sequences

Node	1	2	3	4	5	6	7	8	9	10
1		2,1	3,2,1	4,3,2,1	5,1	6,5,1	7,6,5,1	8,7,6,5,1	9,8,7,6,5,1	10,1
2	1,2		3,2	4,3,2	5,1,2	6,2	7,6,2	8,3,2	9,4,3,2	10,1,2
3	1,2,3	2,3		4,3	5,1,2,3	6,2,3	7,8,3	8,3	9,4,3	10,1,2,3
4	1,2,3,4	2,3,4	3,4		5,1,2,3,4	6,2,3,4	7,8,3,4	8,3,4	9,4	10,1,2,3,4
5	1,5	2,5	3,2,1,5	4,3,2,1,5		6,5	7,6,5	8,7,6,5	9,8,7,6,5	10,11,5
6	1,5,6	2,1,5,6	3,8,7,6	4,3,8,7,6	5,6		7,6	8,7,6	9,8,7,6	10,11,5,6
7	1,5,6,7	2,1,5,6,7	3,8,7	4,3,8,7	5,6,7	6,7		8,7	9,8,7	10,11,12,7
8	1,5,6,7,8	2,3,8	3,8	4,3,8	5,6,7,8	6,7,8	7,8		9,8	10,11,12,7,8
9	1,5,6,7,8,9	2,3,4,9	3,4,9	4,9	5,6,7,8,9	6,7,8,9	7,8,9	8,9		10,11,12,7,8,9
10	1,10	2,1,10	3,2,1,10	4,3,2,1,10	5,11,10	6,5,11,10	7,6,5,11,10	8,7,12,11,10	9,8,14,13,12,11,10	

Based on Figs. 2-4, the first 5 nodes with higher degrees in the optimal network are nodes 14, 8, 12, 7, 13, and the corresponding degrees are 90, 73, 67, 66, 59 respectively. While the first 3 nodes with higher degrees in the initial network are nodes 8, 11, 14, and all the degrees are 4. Although

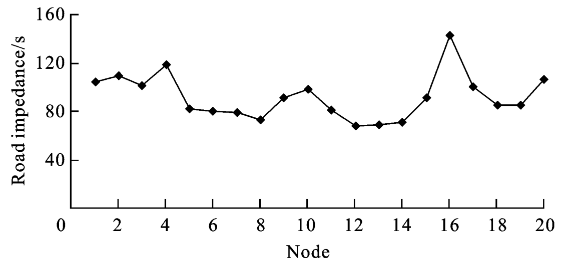

Fig. 2 Road impedances of nodes

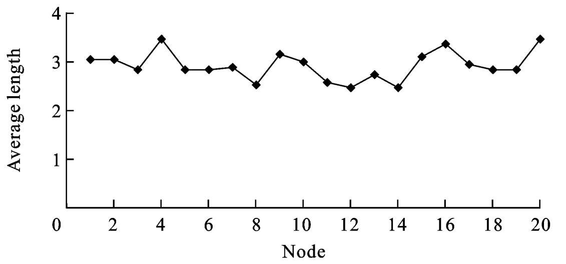

Fig. 3 Average lengths of edges

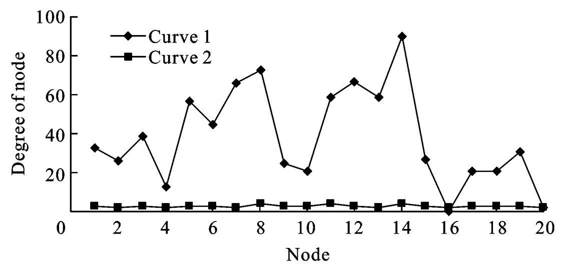

Fig. 4 Degrees of nodes

the number of nodes is smaller, the method in this paper is still a good description of the importance degree of the nodes. However, the degrees of nodes obtained by previous methods, which is subjected to the objective conditions, are often no more than 5. So it is difficult to perceive the importance degree. Based on the survey data, it can be seen that the first 5 nodes with higher degrees in the former method are just the several most important nodes of road network. The main reason is that the central urban area is a commercial center and there is a large number of traffic volume. Meanwhile, the surrounding road network is not sufficient, so it can not effectively alleviate traffic pressure. The average values and standard deviations of node degrees and the road impedances of nodes in the optimal network and the initial network are shown in Tab. 3. In the optimal network, the average value of node degree is 38.750 0, and the standard deviation is 24.683 0. The average road impedance of node is 91.780 0 s, and the standard deviation is 18.862 8 s. But in the initial network, the average value of node degree is 2.850 0, and the standard deviation is 0.670 8. The average road impedance of node is 84.680 0 s, and the standard deviation is 11.768 8 s. The results in the optimal network are far greater than those in the initial network, so the results in the optimal network can reflect the differences effectively. The relationship between the degree and road impedance for node is shown in Fig. 5. Based on the results above, the greater the degree of node is, the smaller the road impedance is.

Tab. 3 Degrees of nodes and average impedances

Network	Degree of node		Road impendance of node	
	Average value	Standard deviation	Average value/s	Standard deviation/s
Optimal network	38.750 0	24.683 0	91.780 0	18.862 8
Initial network	2.850 0	0.670 8	84.680 0	11.768 8

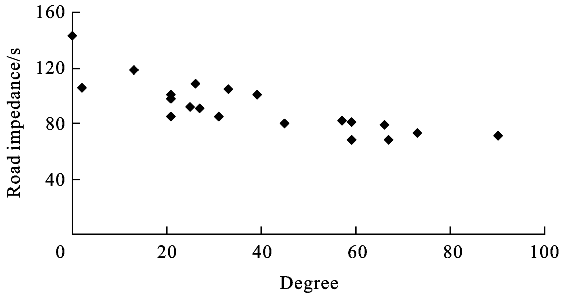

Fig. 5 Retlationship between degree and road impedance for node

Combined Fig. 5 with the actual urban road network, the analysis shows that when nodes with higher degrees in the road network can't play a role steadily, two working conditions will happen. Condition 1 is that the path with the minimum road impedance remains unchanged, when the optimal strategy state is broken, the road impedances of all scattered points must increase or remain, and are impossible to reduce. Therefore, the total road impedances of entire road network will also increase. The traffic efficiency of road network will reduce. Condition 2 is that when the paths with the minimum road impedances change greatly, the sequence of nodes in the initial network will also change greatly. The redistribution of various points in the coordinate system shows that the univariate function in the optimal network is quite different from that in the initial network. The specific circumstances need be recalculated according to the above method. When the road network is under the condition of non-crowded state, the road impedances of many shortest paths increase, and travel costs will increase. It is similar to working condition 1. While the road network is under the condition of crowded state, the paths with the minimum road impendances need to be redistributed, which is similar to the working condition 2. The degrees of edges among different nodes are shown in Tab. 4. The distribution of degrees of edges among different nodes is shown in Fig. 6, it also is the optimal topology network. The coarser the edge is, the more the minimum road impedance is, and the degree of edge in Tab. 4 is corresponding with the coarse size of edge in Fig. 6.

Tab. 4 Degrees of edges among different nodes

Edge	1	2	3	4	5	6	7	8	9	10
Degree	39	37	46	47	8	16	33	19	45	63
Edge	11	12	13	14	15	16	17	18	19	20
Degree	53	42	41	42	55	27	26	53	72	71
Edge	21	22	23	24	25	26	27	28	29	30
Degree	35	21	30	10	55	14	14	32	37	7

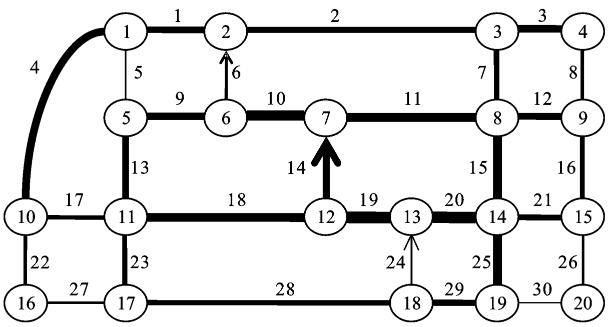

Fig. 6 Distribution of edge degrees among different nodes

Based on the statistical analysis, the average degree of east-west road section is 42.00, and the degrees of edges 10, 18, 19, 20 are higher. The average degree of north-south road secotion is 29.86, and the degrees of edges 4, 10, 55 are higher. It shows that the utilization rate of east-west road section is significantly greater than north-south road section, and the status of east-west road section is relatively uniform. But except some edges have higher degrees, the utilization rates of most north-south road sections are not high. It can be seen that the structure characteristics of road network is focused on east-west road section. Meanwhile, the average degree of internal road section is 55.00, and the average degree of external road section is 28.33. It shows that the traffic pressure of internal road section is too great, and there is not enough peripheral loop to relieve the traffic pressure of internal road section. The analysis shows that the traffic pressures of partial sections are too great, the road network density of central urban area is too low, and there is not enough high grade road on north-south road section, and it causes the phenomenon of vehicle by passing, and the traffic load on east-west road section increases. Compared with the initial network, in the optimal network, not only the physical structure of road network is considered, but also the traffic flow, turn restriction, saturation and some other road traffic characteristics are considered, and vehicle path selection problem is also considered. In the optimal network, the real traffic state in real road network can be truly reflected, and the structural characteristics of road network in different directions and different areas can be reflected. The above results also mean that it can reflect the functions of north-south and east-west road sections, network center and external road sections in road network. So, the optimal topology network can reflect the importance degree of each road section more intuitively and really, and incarnate the difference of road section function. It can provide a theoretical basis for the road network design, road grade division and construction management.

4 Conclusions

Based on the traffic state of real urban road, an initial topology network conversion method is created by Dijkstra algorithm and Space L method, and an optimal network is established. Compared with other topology networks, especially small network, the optimal network has more statistical significance. Meanwhile, the relationship between road impedance and degree for node can be observed clearly and visually by analyzing the relevant characteristic indexes. Analysis result shows that the method can reflect the importance degrees of node and edge in road network objectively and effectively.

From the point of prospect of engineering application, the analysis method of road network structure proposed in this paper is simple and practical. It can be used to analyze generalized travel costs based on delay, emission, energy consumption, traffic safety and many other factors. Because the method is based on the real road network structure by conversing topology network, so it can be used to guide the planning of real road network and traffic management. Moreover, the network conversion method can also be applied in other scientific and engineering fields, such as computer network, biological network, virus propagation network. Further research needs to be combined with other characteristic indexes of complex network.

References:

[1] GUO Ji-fu, GAO Yong, WEN Hui-min. Assessment methodology of connect reliability based on substituted route[J]. Journal of Highway and Transportation Research and Development, 2007, 24(7): 91-94.

[2] CHEN A, YANG Hai, LO H K, et al. Capacity reliability of a road network: an assessment methodology and numerical results[J]. Transportation Research Part B: Methodological, 2002, 36(3): 225-252.

[3] CHEN A, YANG Hai, LO H K, et al. A capacity related reliability for transportation networks[J]. Journal of Advanced Transportation, 1999, 33(2): 183-200.

[4] WATTS D J, STROGATZ S H. Collective dynamics of 'small-world' networks[J]. Nature, 1998, 393(6684): 440-442.

[5] BARABASI A L, ALBERT R. Emergence of scaling in random networks[J]. Science, 1999, 286(5439): 509-512.

[6] ALBERT R, BARABASI A L. Statistical mechanics of complex networks[J]. Reviews Modern Physics, 2002, 74(1): 47-97.

[7] JIANG Bing, CLARAMUNT C. A structural approach to the model generalisation of an urban street network[J]. Geoinformatical, 2004, 8(2): 157-171.

[8] PORTA S, CRUCITT I P, LATORA V. The network analysis of urban streets: a dual approach[J]. Physica A, 2006, 369(2): 853-866.

[9] LAMMER S, GEHLSEN B, HELBIG D. Scaling laws in the spatial structure of urban road networks[J]. Physica A, 2006, 363(1): 89-95.

[10] LATORA V, MARCHIORI M. Efficient behavior of small-world networks[J]. Physical Review Letters, 2001, 87(1): 1-4.

[11] ANDREA D M, MARC B, ALESSANDRO C, et al. The structure of inter-urban traffic: a weighted network analysis[J]. Environment and Planning B: Planning and Design, 2007, 34(5): 905-924.

[12] GAO Zi-you, WU Jian-jun, MAO Bao-hua, et al. Study on the complexity of traffic networks and related problems[J]. Journal of Transportation Systems Engineering and Information Technology, 2005, 5(2): 79-83.

[13] GAO Zi-you, LI Ke-ping, LI Xin-gang, et al. Scaling laws of the network traffic flow[J]. Physica A, 2007, 380(1): 577-584.

[14] JIANG Bing. A topological pattern of urban street networks: universality and peculiarity[J]. Physica A, 2007, 384(2): 647-655.

[15] MA Jia-qi, BAI Yan, HAN Bao-ming. Characteristic analysis of basic unit and complex network for urban rail transit[J]. Journal of Traffic and Transportation Engineering, 2010, 10(4): 65-70.