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Analysis of Urban Road Traffic Network Based on Complex Network

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Abstract

Urban road traffic is a typical network. The analysis and study of the topology structure is the basis of the traffic state evaluation and the traffic organization optimization. This paper redefines the urban road traffic weighted network model with considering the functional properties of urban road network and presents the traffic efficiency concept of the road section in the urban road traffic network. According to the different edge weights which are determined by the different attribute of the edges, we analyses the statistical characteristic of the urban road traffic network based on the three different network models which include the length weighted network model, the traffic capacity weighted network model and the traffic efficiency weighted network model. We take Beijing road traffic network as an example to illustrate the effectiveness of the analysis methods for the structural characteristics.

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Keywords: urban road traffic; complex network; topological structure

1. Introduction

With the enlarging urban scale, the rapid increase of people living in cities brings tremendous pressure to the urban road traffic. The widespread traffic congestion is now nearly ubiquitous in many urban areas. The congestion not only affects the mobility of travellers, but also may increase the considerable external costs such as pollution,

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noise and road user safety. The optimal modification and the intelligent management of urban traffic are effective ways to ease traffic congestion. So it is important significance to analysis and research the urban road traffic network.

Urban road network is a typical spatial network because of its geographical factors. The nodes and edges are embedded in space. It's easiest to understand that the urban road network model is built in which the nodes mean the intersections and the edges mean the road sections by which the two intersections can be connected directly. The topology of the urban road network is analysed by many researchers (e.g. Jiang et al. [1]). The edges in this network are often real physical constructs (e.g. Mukherjee [2]). Gastner et.al [3] studied networks that connect points in geographic space and found that there are strong signatures in these networks of topography. De Montis et.al [4] used a weighted network model to study the structure of the road network representing the interurban commuting traffic of the Sardinia region, analysed both the topological and weighted properties of the resulting network quantitatively and discussed the interplay between the topological and dynamical properties of the network as well as their relation with socio-demographic variables such as population and monthly income. There are lots of research papers to work on the dual graph of the urban road network. The dual network model with the roads as the nodes and the intersections as the edges can be constructed to explore some meaningful results. Masucci et.al [5] studied the growth of London's street network in its dual representation and showed that the growth of the network can be analytically described by logistic laws and that the topological properties of the network are governed by robust log-normal distributions characterizing the network's connectivity and small-world properties that are consistent over time. Zheng et.al [6] analysed the topological properties of Beijing public transport network and found that the node strength, ordinal number and cumulative strength distribution of the nodes all follow the power-law distribution showing the network characteristics of scale-free and small world.

2 Urban road traffic network

2.1 Related work

In an unweighted network, the relationship between the nodes can be described based on two-valued logic. It is set to 1 when the two nodes are connected directly; otherwise it is set to 0. The unweighted network simplifies the complexity of the actual network. It is helpful to analyze the topological properties of the complex network. But the heterogeneity of the complex network is ignored such as the connection strength and density. The connection strength heterogeneity is usually the important characteristics for some complex networks (e.g. Wu et al. [7]). Each edge has a connection strength value in the weighted network. The weights and their distribution have a significant impact on the nature and function of the network. Also they can help understand the nature and function of the complex systems more deeply.

The study of complex networks is a young and active area of scientific research inspired largely by the empirical study of real-world networks such as computer networks and social networks (e.g. Kim et al. [8]). The research content mainly includes the geometrical properties of the networks, the formation mechanism of the networks, the statistical regularities of the network evolution, the stability of the network architecture, the dynamic mechanism of the network evolution and so on (e.g. Watts et al. [9]; Barabasi et al. [10]). Many quantities and measures of complex networks have been proposed and investigated in the past few years which include the degree distribution, the degree-degree correlation, the clustering coefficience, the average path length, the betweenness and so on (e.g. Boccaletti et al. [11]).

2.2 Urban road traffic weighted network model

Based on the physical topology model of the urban road traffic network, we redefine the urban road traffic weighted network with considering the functional properties of urban road network such as the length and traffic capacity of the road sections.

$$URTN = (N, E, EL, ETC) \tag{1}$$

where, (1) $N = \{n_1, n_2, n_3, \cdots, n_n\}$ is the finite set of the nodes which means the intersections, n is the number of the intersections, (2) $E = \{e_{ij} \mid i, j \in N\}$ is the finite set of the edges that means the sections of the road by which the two intersections can be connected directly, e is the number of elements in set E and means the number of the road sections, $e_{ij} \neq e_{ji}$,(3) $EL : E \to R^+$ is the mapping function from an edge to a positive real number, $EL(e_{ij}) = l_{ij}$ is the length of the road section e_{ij}, (4) $ETC : E \to Z^+$ is the mapping function from an edge to a positive integer, $ETC(e_{ij}) = tc_{ij}$ is the traffic capacity of the road section e_{ij}.
The value of l_{ij} and tc_{ij} can be determined as following.

$$l_{ij} = \begin{cases} r_{ij}, & e_{ij} \in E \\ \infty, & e_{ij} \notin E \end{cases}, \quad r_{ij} \in R^+ \tag{2}$$

$$tc_{ij} = \begin{cases} z_{ij}, & e_{ij} \in E \\ 0, & e_{ij} \notin E \end{cases}, \quad z_{ij} \in Z^+ \tag{3}$$

2.3 Traffic efficiency

All kinds of the real-world network can realize their basic function due to the function implementation of the nodes and edges. In the urban road traffic network, the functional properties of the road sections, such as the length and traffic capacity, have meaning of the decision to ensure the timing of the urban residential travelling.
Definition 2. The traffic efficiency of the edge e_{ij} is defined as the ratio of the traffic capacity to the length of the road section e_{ij}, as shown in

$$E_{ij} = \frac{tc_{ij}}{l_{ij}} \tag{4}$$

The traffic efficiency of the road traffic is inversely proportional to the length which means that the road section can implement the transit capacity more efficiently with the shorter length, but it is proportional to the traffic capacity which indicates that the road section can implement the transit capacity more efficiently with the greater traffic capacity.

3 Structural characteristics analysis

3.1 Length weighted network model

The length weighted network model is represented as $URTN_l = (N, E, EL)$ which is a simplified model of $URTN = (N, E, EL, ETC)$.
The edge length weight describes the length of the road section between two intersections. The length weight of the edge e_{ij} is marked as $w_l(e_{ij})$. We can obtain the length weight of the edge e_{ij} by the following formula.

$$w_l(e_{ij}) = l_{ij} \tag{5}$$

The node distance degree describes the total length of the adjacent road sections of the intersection. We can obtain the distance degree, the distance input degree and the distance output degree of the node n_k by the following formulas.

$$d_l(n_k) = \frac{1}{2} \sum_{i \in vn(n_k)} (w_l(e_{ik}) + w_l(e_{ki})) \quad (6)$$

$$d_l^{in}(n_k) = \sum_{i \in vn(n_k)} w_l(e_{ik}) \quad (7)$$

$$d_l^{out}(n_k) = \sum_{i \in vn(n_k)} w_l(e_{ki}) \quad (8)$$

where, $vn(n_k)$ is the set of the neighbor nodes of the node n_k .

The node average shortest distance path length describes the average length of the shortest distance path which the urban residents from the intersection can arrive at the any other intersections. We can obtain the average shortest distance path length of the node n_k by the following formula.

$$asp_l(n_k) = \frac{1}{n-1} \sum_{i=1, i \neq k}^{n} sp_{k-i}^l \quad (9)$$

where, sp_{k-i}^l is the length of the shortest distance path from the node n_k to the node n_i .

The average distance path length of the urban road traffic network $URTN_2$ can be obtained by the the following formula.

$$asp_l^*(URTN_2) = \frac{1}{n} \sum_{i=1}^{n} asp_l(n_i) \quad (10)$$

3.2 Traffic capacity weighted network model

The traffic capacity weighted network model is represented as $URTN_3 = (N, E, ETC)$ which is a simplified model of $URTN = (N, E, EL, ETC)$.

The edge capacity weight describes the traffic capacity of the road section between two intersections. We can obtain the capacity weight of the edge e_{ij} by the following formula.

$$w_c(e_{ij}) = tc_{ij} \quad (11)$$

The node capacity degree describes the total traffic capacity of the adjacent road sections of the intersection. We can obtain the capacity degree, the capacity input degree and the capacity output degree of the node n_k by the following formulas.

$$d_c(n_k) = \frac{1}{2} \sum_{i \in vn(n_k)} (w_c(e_{ik}) + w_c(e_{ki})) \quad (12)$$

$$d_c^{in}(n_k) = \sum_{i \in vn(n_k)} w_c(e_{ik}) \quad (13)$$

$$d_c^{out}(n_k) = \sum_{i \in vn(n_k)} w_c(e_{ki}) \quad (14)$$

3.4 Traffic efficiency weighted network model

The traffic efficiency weighted network model is represented as $URTN = (N, E, EL, ETC)$.

The edge efficiency weight describes the traffic efficiency of the road section between two intersections. The efficiency weight of the edge e_{ij} is marked as $w_e(e_{ij})$ wihch can be obtained by by the following formula.

$$w_e(e_{ij}) = E_{ij}^1 = \frac{E_{ij}}{mean\{E_{pq} \left| e_{pq} \in E\right\}} \tag{15}$$

where, $mean\{E_{pq} \left| e_{pq} \in E\right\}$ is the average traffic efficiency of the all road sections in the urban road traffic network.

The node efficiency degree describes the total traffic efficiency of the adjacent road sections of the intersection. We can obtain the efficiency degree, the efficiency input degree and the efficiency output degree of the node n_k by the following formulas.

$$d_e(n_k) = \frac{1}{2} \sum_{i \in vn(n_k)} (w_e(e_{ik}) + w_e(e_{ki})) \tag{16}$$

$$d_e^{in}(n_k) = \sum_{i \in vn(n_k)} w_e(e_{ik}) \tag{17}$$

$$d_e^{out}(n_k) = \sum_{i \in vn(n_k)} w_e(e_{ki}) \tag{18}$$

The node average optimal path length describes the average length of the optimal path which the urban residents from the intersection can arrive at the any other intersections. It can be obtained by the following formula.

$$asp_e(n_k) = \frac{1}{n-1} \sum_{i=1, i \neq k}^{n} sp_{k-i}^{e} \tag{19}$$

where, sp_{k-i}^{e} is the length of the optimal path from the node n_k to the node n_i . Because the edge efficiency weight is a similarity weight, we should use the reciprocals of the edge efficency weight as a revised edge length weight to calculate the optimal path. The revised length weight of the edge e_{ij} can be obtained by the following formula.

$$w_e^l(e_{ij}) = \frac{1}{E_{ij}^1} \tag{20}$$

The network optimal path length describes the length of the the optimal path between two intersections which is averaged over all pairs of intersections. The optimal path length of the urban road traffic network $URTN$ can be obtained by the the following formula.

$$asp_e^*(URTN) = \frac{1}{n} \sum_{i=1}^{n} asp_e(n_i) \tag{21}$$

4 Case study

4.1 Beijing road traffic network

The road traffic network of Beijing is shown in Fig. 1. The field data which include the dynamic data and the static data are from the Beijing Municipal Traffic Management Bureau. The raw information is collected form the road traffic sensor network with 2058 sensors which can be seen as the 2058 small road sections. The road traffic sensor network in Beijing is shown in Fig.1(a). We build Beijing road traffic network model wtih 167 nodes and 582 edges based on the road traffic sensor network. It is shown in Fig.1(b). The nodes include the intersections and the boundary point (the city boundary point, the end of the dead end highway and so on). The edges are the road sections between the adjacent nodes. Here, it points out that the node number has the certain regularity. The node numbering increases from the nodes outside Sixth Ring Road to the nodes inside Second Ring Road.

a b

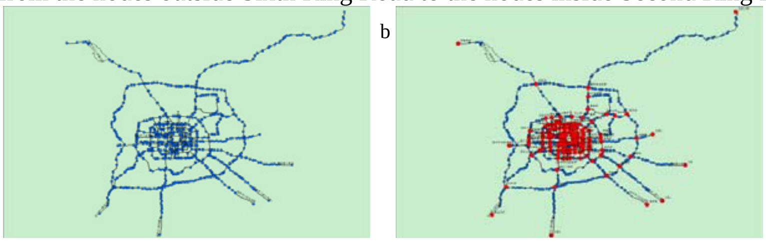


Fig. 1. Beijing Road Traffic Network.

4.2 Structural characteristics analysis of Beijing length weighted network model

The edge length weight and the node distance degree in the Beijing length weighted network model and their distribution are shown in Fig. 2. The length weight of each edge is shown in Fig. 2(a). It's easy to see that the lengths of the road sections on Sixth Ring Road and outside Sixth Ring Road have much larger values. In other words, there are almost the long-distance road sections outside Fifth Ring Road and the short-distance road sections inside Fifth Ring Road. The edge length weight distribution is shown in Fig. 2(b). We can see that the road sections less than 0.1 *hkm* are more than 500 or about 90% of all road sections in the Beijing road traffic network. It shows clearly that there are lots of short-distance road sections and very few long-distance road sections in Beijing. The distance degree of each node is shown in Fig. 2(c). It's easy to see that the distance degree of the intersections outside Fifth Ring Road have much larger values and the distance degree of the intersections inside Fifth Ring Road have much smaller values. That is to say, the distance of the intersection outside Fifth Ring Road between it and the adjacent intersections is much longer than the intersections inside Fifth Ring Road. The node distance degree distribution is shown in Fig. 2(d). We can see that the intersections with the distance degree less than 0.2 *hkm* are more than 135 or about 80% of all intersections in the Beijing road traffic network. It shows clearly that there are lots of intersections with short-distance adjacent road sections and few intersections with long-distance adjacent road sections in Beijing.

The node average shortest distance path length and its distribution in the Beijing length weighted network model are shown in Fig. 3. The shortest distance path lengths between any two nodes are shown in Fig. 3(a). It describes the length of the shortest distance path through which the urban residents can arrive at the destination intersection from the origin intersection. We can see that the shortest diatance path lengths between any two intersections on Sixth Ring Road and outside Sixth Ring Road have much larger values. There are the opposite results for any two intersections inside Sixth Ring Road. The shortest diatance path lengths between the intersections inside Sixth Ring Road and the intersections outside Sixth Ring Road have relatively larger values. The minimum, maximum and average shortest diatance path length of the intersection among the all shortest path length between it and the any other intersection are shown in Fig. 3(b). It shows that the intersections outside Sixth Ring Road have the same regularity. The minimum shortest diatance path lengths of the intersections outside Sixth Ring Road is more than 0.1 *hkm* and the average value is more than 0.3 *hkm* . The another same rule of the intersections inside Sixth Ring

Road is that the minimum shortest diatance path lengths is less than 0.1 *hkm* and the average value is less than 0.3 *hkm* . The maximum shortest diatance path lengths of the intersections have no obvious regularity. But they must be the shortest diatance path lengths between any one intersection and the intersection outside Sixth Ring Road. The average shortest distance path length distribution of the intersections is shown in Fig. 3(c). It's easy to see that there are almost 80% intersections in the Beijing road traffic network departing from which the urban residents can averagely arrive at any other intersection through the shortest distance path with the length less 0.2 *hkm* .

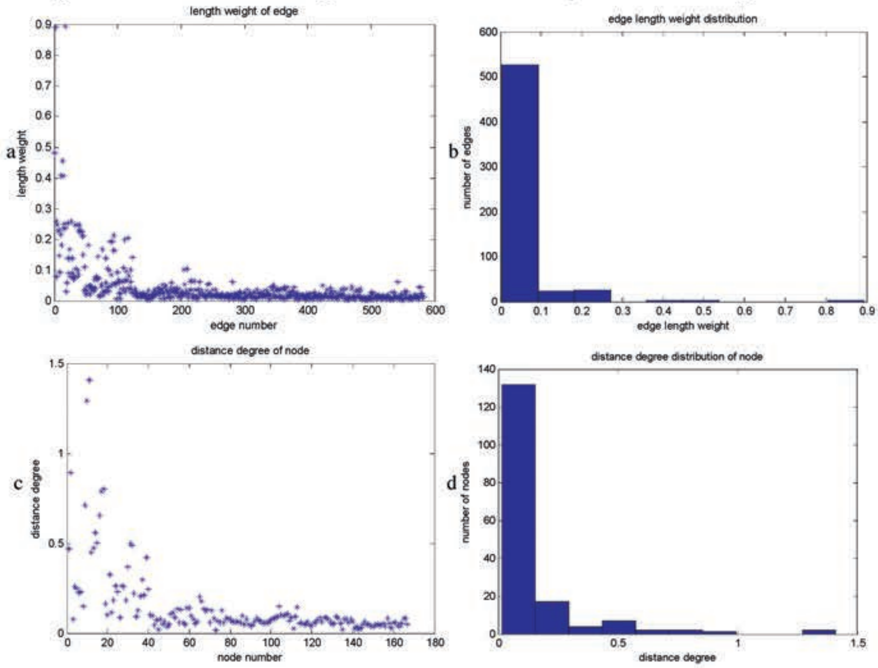


Fig. 2. Edge length weight and node distance degree in Beijing length weighted network model.

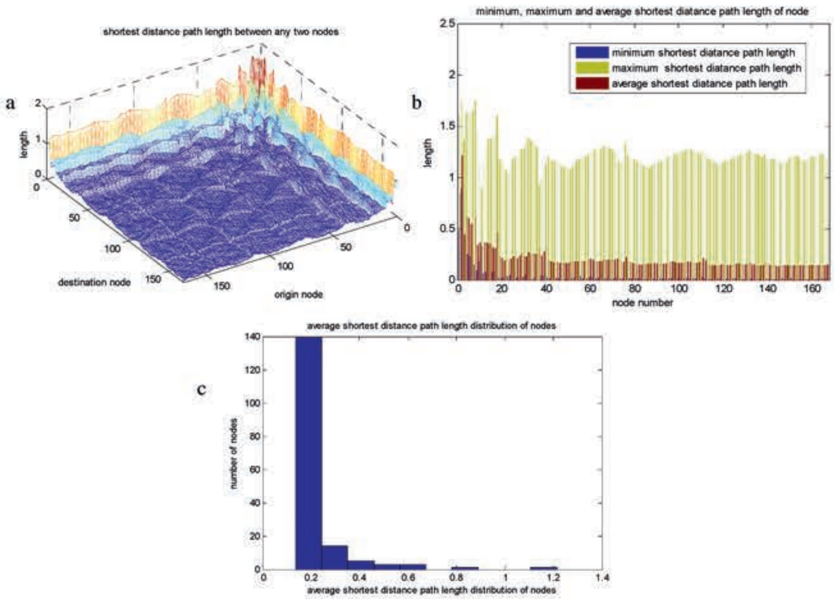


Fig. 3. Node average shortest distance path length and its distribution in Beijing length weighted network model.

4.3 Structural characteristics analysis of Beijing traffic capacity weighted network model

The edge capacity weight and the node capacity degree in the Beijing traffic capacity weighted network model and their distribution are shown in Fig. 4. The capacity weight of each edge is shown in Fig. 4(a). It's easy to see that the road sections outside Sixth Ring Road and inside Second Ring Road have the lower traffic capacities. The traffic capacities of the other road sections have higer values. The edge capacity weight distribution is shown in Fig. 4(b). We can see that the road sections with the traffic capacities between 4000 *pcu* and 7500 *pcu* are more than 400 or about 70% of all road sections in the Beijing road traffic network. These road sections are located between Fifth Ring Road and Second Ring Road (including on these two roads). The road sections with the traffic capacities less than 2000 *pcu* are about 80. Almost of them are old city streets located inside Second Ring Road, A few of them are old suburban highways located outside Fifth Ring Road. The capacity degree of each node is shown in Fig. 4(c). It's easy to see that the intersections with higher traffic capacity are located between Fifth Ring Road and Second Ring Road (including on these two roads). The adjacent road sections of these intersections always have higher traffic capacity. The node capacity degree distribution is shown in Fig. 4(d). We can see that the intersections with capacity degree between 10000 *pcu* and 30000 *pcu* are about 130 or 75% of all intersections in the Beijing road traffic network. But the intersections with capacity degree lower 10000 *pcu* are about 33 or 20% of all intersections in the Beijing road traffic network

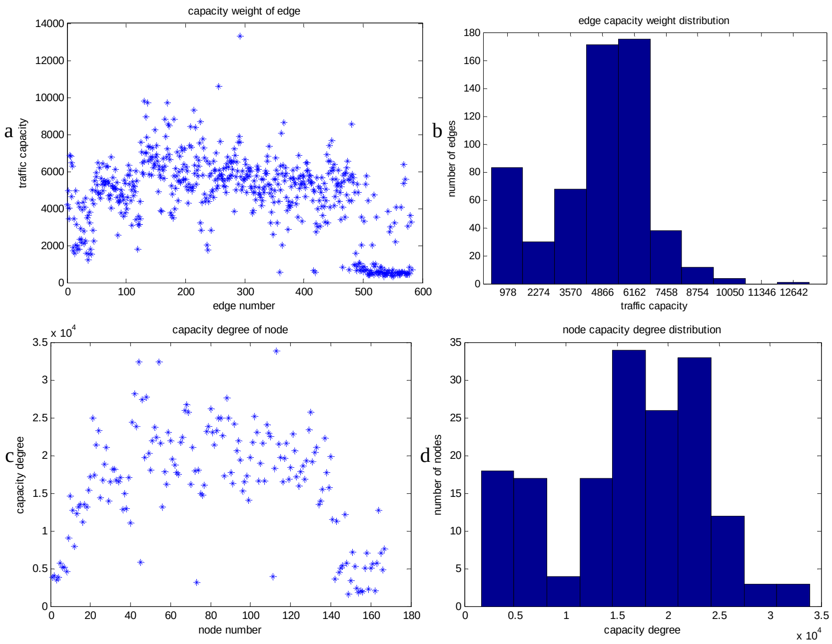
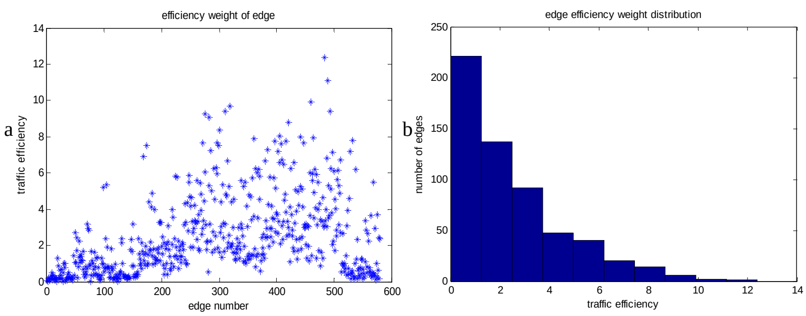


Fig. 4. Edge capacity weight and node capacity degree in Beijing traffic capacity weighted network model.



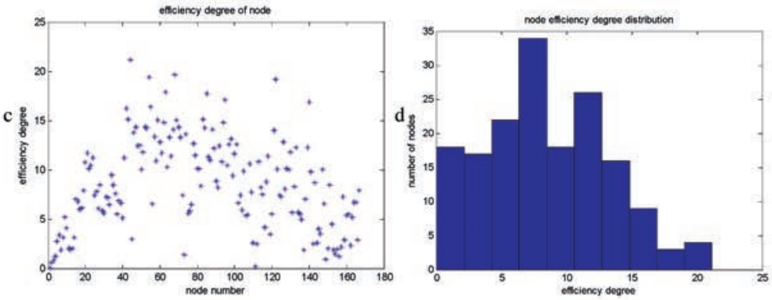
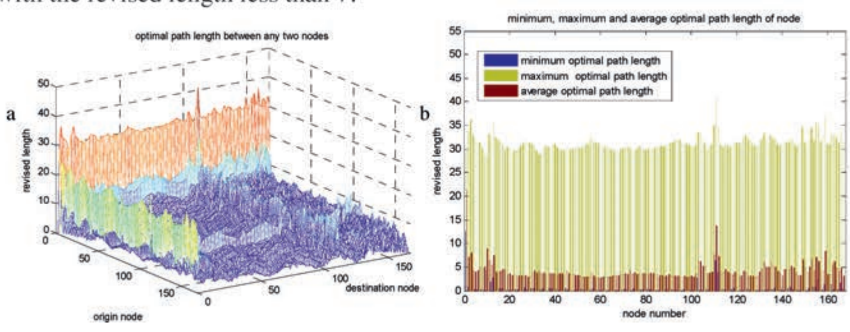


Fig. 5. Edge efficiency weight and node efficiency degree in Beijing traffic efficiency weighted network model.

4.4 Structural characteristics analysis of Beijing traffic efficiency weighted network model

The edge efficiency weight and the node efficiency degree in the Beijing traffic efficiency weighted network model and their distribution are shown in Fig. 5. The efficiency weight of each edge is shown in Fig. 5(a). It's easy to see that the road sections outside Fourth Ring Road and inside Second Ring Road have the lower traffic efficiency. These road sections always have longer distances or lower traffic capacities. The edge efficiency weight distribution is shown in Fig. 5(b). It is similar to a power-law distribution. There are a great many road sections with lower traffic efficiency and a very few road sections with higher traffic efficiency. The efficiency degree of each node is shown in Fig. 5(c). The traffic efficiency degrees of the intersections outside Sixth Ring Road are generally lower. The node efficiency degree distribution is shown in Fig. 5(d). Excepting the several intersections with much higer traffic efficiency, the traffic efficiency degree distribution of the other intersections is similar to an uniform distribution.

The node average optimal path length and its distribution in the Beijing traffic efficiency weighted network model are shown in Fig. 6. The optimal path lengths (the revised length) between any two nodes are shown in Fig. 6(a). It describes the length of the optimal path through which the urban residents can arrive at the destination intersection from the origin intersection. We can see that the optimal path lengths between any two intersections inside Sixth Ring Road have smaller values. But the optimal path lengths between the intersections inside Sixth Ring Road and the intersections outside Sixth Ring Road have larger values. The minimum, maximum and average optimal path length of the intersection among the all shortest path length between it and the any other intersection are shown in Fig. 6(b). It shows that the average optimal path lengths of the intersections outside Sixth Ring Road have larger value. The node 111 (BALIZHUANGQIAO) between Third Ring Road and Forth Ring Road also has a very higher value. Because this node is the end of the dead end highway and the edge between it and its single neighbouring node 112 (CHEDAOGOUQIAO) has a lower traffic efficiency. The average optimal path length distribution of the intersections is shown in Fig. 6(c). It's easy to see that therw are almost 80% intersections in the Beijing road traffic network departing from which the urban residents can arrive at any other intersection through the optimal path with the revised length less than 7.



c

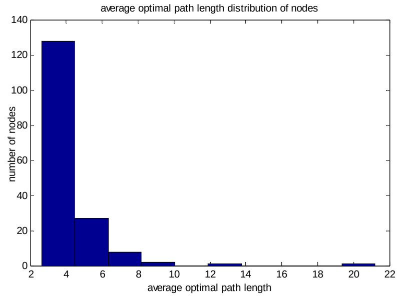


Fig. 6. Node average optimal path length and its distribution in Beijing traffic efficiency weighted network model.

5 Conclusion and Future Work

This paper first redefines the urban road traffic weighted network model with considering the functional properties of urban road network and presents the traffic efficiency concept of the road section in the urban road traffic network. Next the structural characteristics analysis of the urban road traffic network is provided based on the following three models: the length weighted network model, the traffic capacity weighted network model and the traffic efficiency weighted network model. Finally we take the urban road traffic network of Beijing as an example to analyze the structural characteristics of the road traffic network. The main works of this paper are completed based on the static datas. In the future works, we will use the dynamic datas to analyze the changing structural properties of the urban road traffic network.

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