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Complex Network Analysis of Guangzhou Metro

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Abstract

The structure and properties of public transportation networks can provide suggestions for urban planning and public policies. This study contributes a complex network analysis of the Guangzhou metro. The metro network has 236 kilometers of track and is the 6th busiest metro system of the world. In this paper topological properties of the network are explored. We observed that the network displays small world properties and is assortative in nature. The network possesses a high average degree of 17.5 with a small diameter of 5. Furthermore, we also identified the most important metro stations based on betweenness and closeness centralities. These could help in identifying the probable congestion points in the metro system and provide policy makers with an opportunity to improve the performance of the metro system.

Keywords: Guangzhou metro, complex networks, betweenness centrality, closeness centrality.

Introduction

Transportation systems as part of the infrastructure are an integral part to the overall development of a country and is are important determinants of economic growth owing to the fact that it is vital for tourism industry, ensures mobility of goods and people across the country, thereby placing the economy on its growth path. During the past few years, complex network analysis has been used to study different networks including the neural networks [1], communication networks [2, 3], power grids [4], and transportation systems including the air networks [5,6,7,8], railway networks [9, 10], public transportation in Singapore [11] and Poland

[12], and the underground transportation in Boston and Vienna [13, 14]. While some of the studies have focused on the dynamic properties of complex network, most of the works in the literature of complex networks have focused on the characterization of topological properties such as the small world behavior and scale free structure [15]. In this paper, we study the topological properties of the Guangzhou Metro. The network, which transfixes all directions with 236 kilometers of tracks, has been formed in Guangzhou, with an average passenger capacity of 3,240,000 passenger trips per day. Having delivered 1.85 billion rides in 2012, Guangzhou Metro is the sixth busiest metro system in the world, after the metro systems of Tokyo, Seoul, Moscow, Beijing, and Shanghai [16].The rest of the paper is laid out as follows. In section 2 we discuss the network construction and the topological properties of the network whereas section 3 concludes the paper.

Network Construction and Topological properties

The Guangzhou metro consists of N = 144 stations extending across Guangzhou city. Two different methodologies exist in common literature for the representation of a network as a graph. The first methodology (space L) consists of nodes representing stations and a link between two nodes exists if they are consecutive stops on the route. Secondly, although nodes in the second methodology (space P) are the same as in the previous topology, here an edge between two nodes means that there is a direct route that links them. We adopt the second methodology and hence our network can be considered as a graph with N nodes and K edges and is represented by the adjacency matrix $\{a_{ij}\}$, i.e., the $N \cdot N$ matrix whose entry a_{ij} is 1 if and only if there is an edge directly joining node i to node j and 0 otherwise. Table 1shows all the computed network statistics, from basic network properties such as the number of nodes and edges to the more complex analysis such as clustering, assortativity and centralities.

Table 1: Computed Properties of Guangzhou Metro

Property	Value
Nodes, N	144
Edges, M	1137
Average path length, (l)	2.6
Average Clustering coefficient, C	0.95
Diameter, d	5
Average degree	17.5
Degree range	(8, 45)
Assortativity, r	0.32
Betweenness Centrality	0.01
Closeness Centrality	0.003

We start off with the average shortest path length. The average shortest path length

(The minimum number of edges passed through to get from one node to another) between one node to all other nodes of the network is calculated using the following equation:

$$D = \sum_{s,t \in V} \frac{d(a,b)}{N(N-1)} \quad (1)$$

Where,

V = set of nodes in the network,
d (a, b) = shortest path from *a* to *b*
N = total number of nodes in the network.

A small average path length of a single stop (l = 2.6) means that there is travel among almost all the stations of Guangzhou Metro, regardless of geographical distance. The network also features small diameter (maximum path length of a network) d = 5. The degree of a node, a measure of its connectivity, is defined as the fraction of nodes with degree k in the network. In our case, the degree is defined as the number of stations that can be reached from a given station via a single route. For a given node i, the degree can be represented using:

$$k_i = \sum_{j}^{N} a_{ij} \quad (2)$$

The average degree of the whole graph can thus be obtained using the following equation:

$$\langle k \rangle = \frac{1}{N}\sum_{i}^{N} k_i = \frac{1}{N}\sum_{i}^{N}\sum_{j}^{N} a_{ij} \quad (3)$$

The network possesses a high average degree of 17.5, indicating high connectivity among the nodes. The degree distribution of the network is presented in Fig. 1.

Clustering coefficient (C_i) of a node i is defined as the ratio of the number of mutually shared links by its neighboring nodes to the highest number of potential probable links among them. The average clustering coefficient is defined as

$$\langle C \rangle = \frac{1}{N}\sum_{i=0}^{N} C_i \quad (4)$$

Using the above equation, the average clustering coefficient (C) of the network is calculated to be 0.95, indicating that the Guangzhou metro is a highly clustered network. This result is substantially higher than the value of an equivalent Erdös–Rényi random graph, (C_{ER}) = 0.06. The clustering coefficient together with the small average path length (see above) indicates that the Guangzhou metro is a small-world.

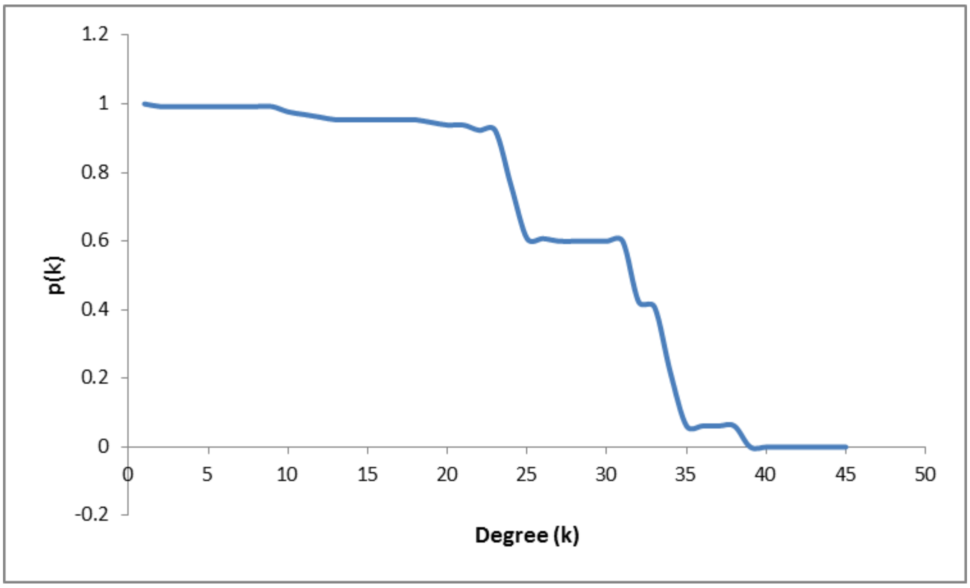

Figure 1. Degree Distribution

Degree – degree correlation is another important structural characteristic of a network which demonstrates the tendency of nodes connecting to either high-degree or low-degree nodes or assortative and disassortative nature of the network. Assortative networks are networks where high-degree nodes connect to other high degree nodes in the network. A disassortative network is one where low degree nodes show a tendency to connect to other high-degree nodes. This characteristic of the network can be computed using the Pearson correlation coefficient, introduced by Newman in 2002 [17]. Mathematically, this expression can be represented by the following equation.

$$r = \frac{1}{\sigma_q^2} \sum_{jq} jk \left(e_{jk} - q_j q_k \right) \quad (5)$$

Where

$$q_k = \sum_j e_{jk} \text{ and } \sigma_q^2 = \sum_k k^2 q_k - \sum_k k q_k^2 \quad (6)$$

This statistic lies in between the range of [-1, 1], where −1 indicates a completely disassortative network and 1 indicates a completely assortative network. For Guangzhou metro, the assortativity is measured to be 0.32 illustrating high degree nodes at one end of a link showing preference towards high degree nodes at the other end. A closer inspection of the degree correlations can be done using another measure, the average degree of nearest neighbor, $K_{nn}(k)$ for nodes of degree k.

$$k_{nn,\,i} = \frac{1}{k_i} \sum_{j=1}^{N} a_{ij} k_j \quad (7)$$

If $k_{nn}(k)$ increases with k, the network is assortative. If $k_{nn}(k)$ decreases with k, the network is disassortative. Fig. 2 represents the average degree of nearest neighbor and it can be seen that the $k_{nn}(k)$ increases with degree k, which is consistent with a positive assortativity of 0.32. To identify the stations with high congestion, betweenness centrality is used. Betweenness centrality of a node i can be defined as sum of the fraction of all-pairs shortest paths that passes through i. Mathematically:

$$c_B(i) = \sum_{s,t \in V} \frac{\sigma(s,t \mid i)}{\sigma(s,t)} \quad (8)$$

Where V is the set of nodes, $\sigma(s, t)$ is the total number of shortest paths and $\sigma(s,t|i)$ is the number of shortest paths passing through i [18]. Betweenness centrality is presented in Fig. 3 whereas the top ten metro stations according to high betweenness centrality are given in Table 2. The interchange Tiyu Xilu leads the list as it provides a link between three different subway lines and hence has the largest congestion. The other interchanges following Tiyu Xilu are Chebeinan, Xilang, Yangji and Guangzhou Railway Station. Another studied parameter is the Closeness centrality, defined as the average shortest distance from node i to all the other nodes, which reflects the closeness degree of the node with other nodes in the network. The mathematical expression is

$$C(V_i) = \frac{(N-1)}{\sum_{j=1}^{n} d(V_i V_j)} \quad (9)$$

Where $d(V_iV_j)$ is the shortest distance between V_i and V_j and is equal to the minimum stations from V_i to V_j in the network whereas $(N\text{-}1)$ is the normalization factor. Closeness centrality reflects the closeness degree from one station to all the other stations in the underground metro network, the larger the value, the greater influence and the wider range of service the station has. The top ten stations based on closeness centrality are listed in table 3 whereas in figure 4 we have plotted the closeness of the nodes as a function of degree k.

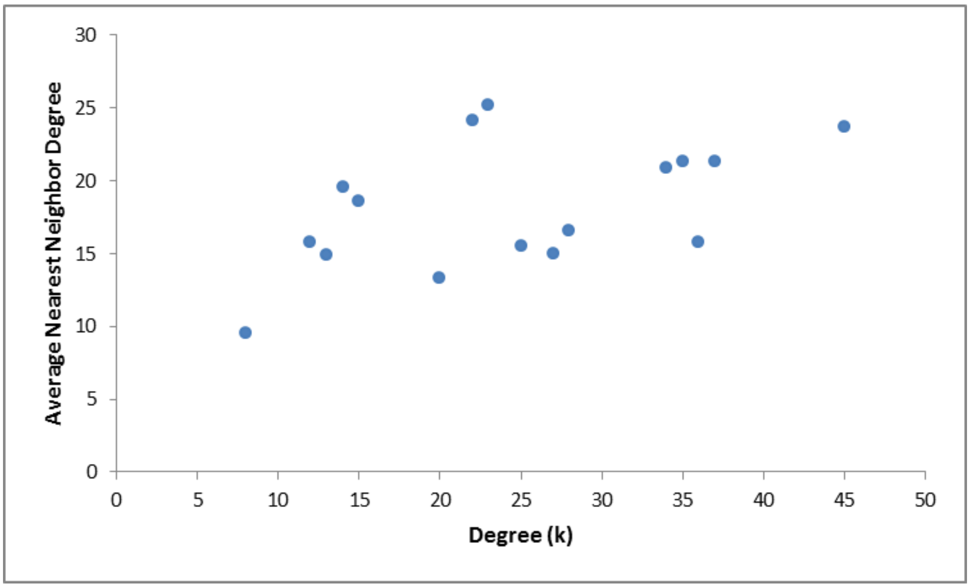

Figure 2. Average Nearest Neighbor Degree

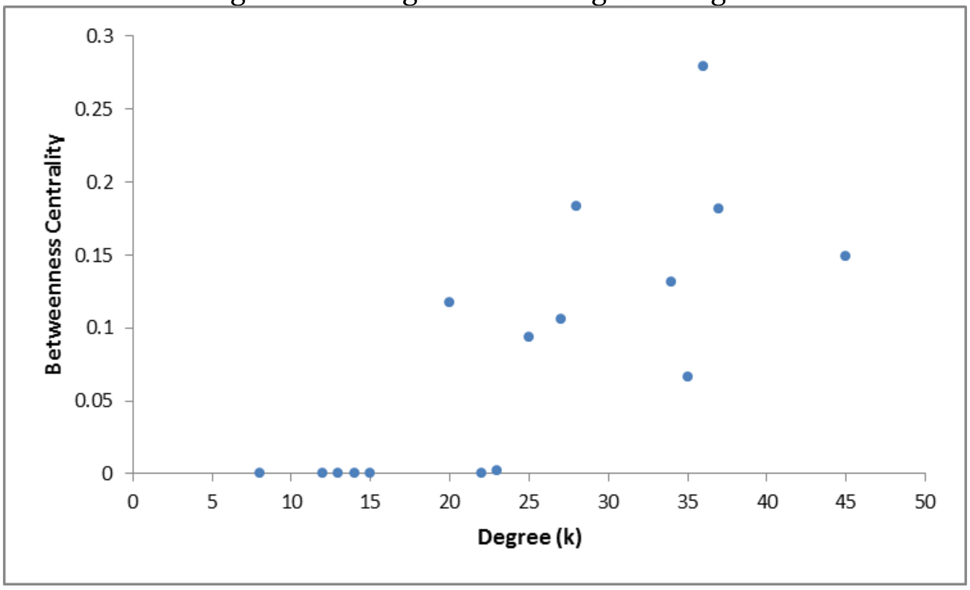

Figure 3. Betweenness Centrality

Conclusions and future work

In this paper we have studied the Guangzhou metro as an unweighted graph of metro stations. The degree distribution is observed to be neither a power law nor normal. The network clearly displays small-world properties and is assortative in nature. The betweenness and closeness centralities of the stations are also computed, wherein these stations are identified as potential congestion points. As public transportation especially the underground metro provide crucial mode of movement of passengers, the identification of possible congestion stations may help in identifying the limitations of the network. Although this study contributes a complex network analysis of the physical state of the Guangzhou metro, given the availability of passenger flow data, it would also be interesting to study the weighted network as it could reveal a clearer picture of network dynamics in terms of passenger flow. Such a study would not only reveal the topological aspects but also provide a detailed insight into the network dynamics by identifying the stations with greater flow, the correlations of the edge weights with the degree of the vertices and especially the eigenvector centrality which states that the quality of an edge should matter, i.e., an edge to a highly central node should matter more than an edge to a node with low centrality.

Table 2: Betweenness Centrality of Top Ten Stations

Betweenness Centrality	Metro Stations
0.28	Tiyu Xilu
0.18	Chebeinan
0.18	Xilang
0.18	Yangji
0.15	Guangzhou Railway Station
0.14	Kecun
0.13	Jiahewanggang
0.12	Linhexi
0.11	Wanshengwei
0.07	Gongyuanqian

Table 2: Closeness Centrality of Top Ten Stations

Closeness Centrality	Metro Stations
0.004	Tiyu Xilu
0.004	Yangji
0.004	Guangzhou Railway Station
0.004	Jiahewanggang
0.004	Guangzhou East Railway Station
0.004	Xilang
0.004	Gongyuanqian
0.003	Tianhe Sports Center
0.003	Dongshankou
0.003	Martyrs Park

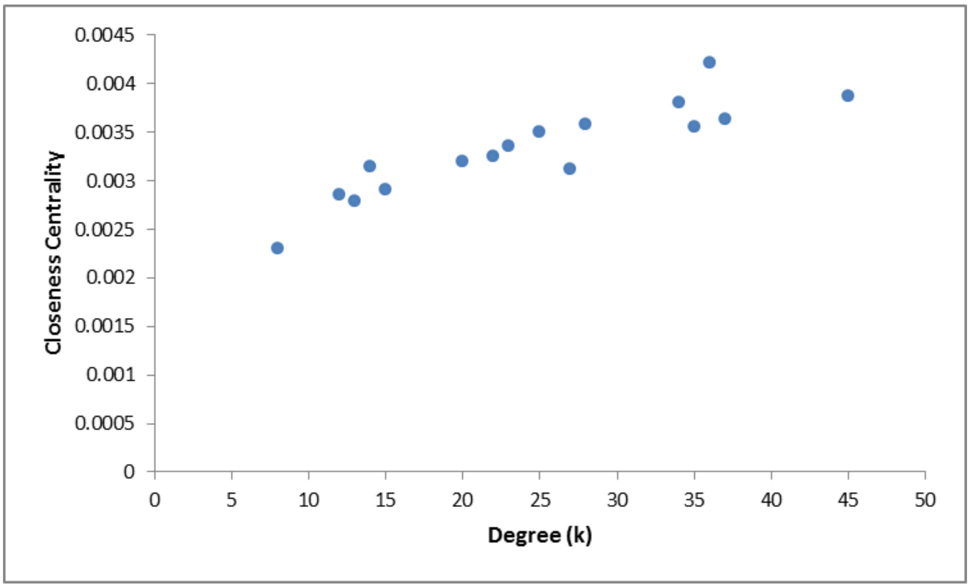

Figure 4. Closeness Centrality

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Комплексный анализ сети метро Гуанчжоу

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Аннотация. Анализируя структуру и особенности сетей общественного транспорта, можно сделать выводы о градостроительной и государственной политики в целом. Данное исследование представляет комплексный анализ сети метро Гуанчжоу. Данная сеть имеет 236 километров трассы и является 6-ой по загруженности системой метрополитена в мире. В работе изучаются топологические свойства сети. Сеть обладает высокой средней степенью 17.5 с небольшим диаметром - 5. Кроме того, мы также определили наиболее важные станции метро на основе соотношения и близости к центру. Эти вопросы могут помочь в выявлении вероятного скопления точек перегрузки в метро и предоставить директивным органам возможность улучшить работу метрополитена.

Ключевые слова: метро Гуанчжоу, совокупность сетей, непосредственная близость, сосредоточенность.