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Correlation between heterogeneity and vulnerability of subway networks based on passenger flow

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ABSTRACT

In this paper, we represent a subway network as a dynamic, directed and weighted graph, where vertices represent subway stations and edge weights represent passenger volume passing between two stations. Static and dynamic metrics which can represent vertices and edges' local and global attributes are proposed. Then dynamic properties of subway network in heterogeneity and vulnerability are further analyzed by standard deviation. Through a detailed analysis of Beijing subway network, we illustrate that the heterogeneity and vulnerability of Beijing subway network vary over time when passenger flow is taken into consideration. In addition, the vulnerability of the network is correlated with its heterogeneity based on local dynamic metric's distribution when passenger flow is taken into account, instead of the global dynamic metric's distribution, and the important station with higher flow degrees are identified.

1. Introduction

With large capacity, high speed, safety, punctuality, energy-saving, environmental protection and other advantages, subway has become the first option to ease urban traffic congestion. With subway lines being constructed and put into operation continuously, some mega-cities comes into subway network operation era, such as Beijing, Shanghai and New York. System theory believes that the system structure determines its function. A well-designed network structure is the basis and prerequisite for the network's good performance. The greater the impact of the some vertices and edges' failure on the whole network is, the more fragile the network structure is, and the greater the risk is.

Complex network approach could describe the structure and behavior of complex systems, and has been used to study the airports, roads, subways and other transportation networks. There are some studies on topological properties of subway network from a graph theory perspective. In Ref (Latora and Marchiori, 2002), Vito Latora assumed that the efficiency in the communication between two nodes is inversely proportional to the shortest distance, and analyzed the small-world of Boston subway. In Ref (Seaton and Hackett, 2004), Katherine A. calculated the clustering coefficient, path length and average vertex degree of two urban train line networks (Boston and Vienna). In Ref (Angeloudis and Fisk, 2006), P. Angeloudis treated subway network as a journey network which was laid on a substrate network of lines, and analyzed the topological properties of world's largest subway systems. In Ref (Derrible and Kennedy, 2010), S. Derrible analyzed the complexity and robustness 33 metro systems in the world, and found that most metros are indeed scale-free (with scaling factors ranging from 2.10 to 5.52) and small-worlds. In Ref (Li and Ma, 2009), L. Jin analyzed some big cities' subway networks' topological properties, and studied the robustness of Beijing subway from three aspects: connectivity, characteristic path length and diameter. In Ref (Deng et al., 2015), Y Deng studied the physical vulnerability of subway

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system. Based on network theory and FMECA method. In Ref (Zhang XuL.Honget al, 2011; Zhang XuL.Honget al, 2013), Zhang JH analyzed and investigated the topological characteristics and functional properties of Shanghai subway network but the network is abstracted as an undirected graph. In Ref (Deng et al., 2013), Y. L Deng investigated the topology vulnerability of Nanjing planned metro in china based on the graph theory complex network theory. In Ref (Denget al, 2013), a multi-functional emergency rescue station planning and siting model was proposed based upon the current metro operation network. In Ref (Yang et al., 2017). X Yang developed a route diversity index for measuring passenger route choice and network vulnerability, the example based on the Beijing Metro network was conducted, they did not consider passenger demand data in assessing the impacts of disruption.

However, a subway network is characterized not only by its topology, but also by the dynamics of passenger flow taking place in the network. In recent years, some studies have looked at the network properties with respect to time and passenger flow. In Ref (Lee et al., 2008), Keumsook Lee analyzed statistical properties and topological consequences of the Metropolitan Seoul subway system, and further studied the passenger flows on the system, and found that the passenger flow weight distribution exhibited a power-law behavior and the degree distribution of the spanning tree of the flows also followed a power law. In Ref (Yin et al., 2016) H. D Yin proposed an estimation method is to analyze network importance where the passenger flows are considered and a case study of Beijing subway is implemented, but when analyzing the disruption impact, the global efficiency and local efficiency adopted Vito Latora's definition where passenger flows were not considered. In Ref (Yang et al., 2015), Y.H Yang took the Beijing Subway system as an example to assess the robustness of a subway network, but several operations such as capacity, flows are not considered in the study. In Ref (Chopra et al., 2016) S. Chopra presented a framework to analyze information on network topology, spatial organization and passenger flow to understand the resilience of the London metro system, and proposed a metric called the fracture coefficient that determines the functional vulnerability of an edge, high fracture coefficient for an edge signified that the system is functionally vulnerable to its disruption, which suggested low resilience. In Ref (Chen et al., 2017), P Chen studied the centrality of urban rail transit network based on passenger flow, and applied this method to the Beijing subway network. In Ref (Cai et al., 2017), H. Cai presented a modified topological vulnerability analysis for the metro network where the flow impacts and the capacity constraint are taken into account and vulnerability of the metro network in Beijing was analyzed, but when defining efficiency of a network, the minimum generalized travel time was proposed to replace the travel cost.

The passenger flow varies over time, the relationship between two the stations varies also and the properties of subway change dynamically. Meanwhile, subway networks display a large heterogeneity in the passenger flow of the connections, and appear more vulnerable to deliberate attacks on highly connected vertices. Therefore, considering the passenger flow, we study the heterogeneity and vulnerability of subway networks from a dynamic perspective. The remainder of this paper is organized as follows. In Section 2, we present the network model for subway stations with dynamic passenger flows. Based on degree and betweenness centralities, dynamic metrics– flow degree and flow betweenness are proposed to represent the vertices and edges' local and global attributes. In Section 3, we introduce standard deviation method to further analyze the heterogeneity and vulnerability of subway networks. In Section 4, we carry out experiments on a case study of the Beijing subway network. Finally, we draw conclusions in Section 5.

2. Construction

The mission of subway is to transport passengers from origin to destination. For subway, the reasons why some stations are congested lie in that the finite network capacity could not satisfy the large number of passengers' demand for traveling. Therefore the model of subway should not only reflect its topology, but also the dynamic passenger flow through the network.

2.1. Network modeling of subway

The physical structure of subway system provide various functions during its daily operation on basis of the stable operation of physical components, and all physical components should function synergistically and collaboratively to produce and distribute a continuous flow of services or products (Takahiro et al., 2007). Space L representation not only provides an understanding of the structural topology and vulnerability, but also allows assessment of impacts of disruptions on a subway network's functionality (transportation of passengers) (Yang et al., 2015). Consequently, in this paper, a dynamic and weighted network of subway that considers passenger flows is built based on subway topology and Space L, where the station is abstracted as vertice and the section between two adjacent stations are abstracted as edge. The model is represented by $G = (V, E, W, P)$, where:

(1) V is the vertices set, $V = \{v_i\}$, $i = 1,2, \cdots N$, v_i stands for the *ith* station in network; N is the numbers of vertices.
(2) E is the edges set, $E = \{e_{ij}\}$, $i, j = 1,2, \cdots N$, $i \neq j$, $e_{ij} = \langle v_i, v_j \rangle$ is an ordered pair composed of two adjacent vertices, which stands for the section linked by the rail track.
(3) W is the weights set, $W = \{\omega_{e_{ij}}(\Delta t)\}$, $\omega_{e_{ij}}(\Delta t)$ stands for the weight of edge e_{ij}, which equals to the passenger volume passing through e_{ij} during a specified time period, Unit: prs/h.

Directionality is a typical characteristic of subway, the weights of edge e_{ij} and e_{ji} are different at the same time, $\omega_{e_{ij}}(\Delta t) \neq \omega_{e_{ji}}(\Delta t)$. As shown in Fig. 1, the passenger volume along different edges-(Taoranting, Caishikou)and (Caishikou, Taoranting) of Beijing Subway varies from 5:00 a.m. to 11:00 p.m. on March 8th, 2013 (Monday). Therefore, the subway network model is a dynamic, directed and weighted model due to the variation of passenger flows.

(4) P is the paths set, $P = \{P_{ij}\}$, $i, j = 1,2, \cdots N$, $i \neq j$, where P_{ij} stands for the paths set from v_i to v_j. There could be more than one path