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Robustness assessment of urban rail transit based on complex network theory: A case study of the Beijing Subway

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ABSTRACT

A rail transit network usually represents the core of a city's public transportation system. The overall topological structures and functional features of a public transportation network, therefore, must be fully understood to assist the safety management of rail transit and planning for sustainable development. Based on the complex network theory, this study took the Beijing Subway system (BSS) as an example to assess the robustness of a subway network in face of random failures (RFs) as well as malicious attacks (MAs). Specifically, (1) the topological properties of the rail transit system were quantitatively analyzed by means of a mathematical statistical model; (2) a new weighted composite index was developed and proved to be valid for evaluation of node importance, which could be utilized to position hub stations in a subway network; (3) a simulation analysis was conducted to examine the variations in the network performance as well as the dynamic characteristics of system response in face of different disruptions. The results reveal that the BSS exhibits typical characteristics of a scale-free network, with relatively high survivability and robustness when faced with RFs, whereas error tolerance is relatively low when the hubs undergo MAs. In addition, illustrations of dynamic variations in the influence of the BSS under a series of MAs were provided by spatial analysis techniques of Geographical Information System (GIS), which directly verified the earlier conclusions. We believed the proposed methodology and the results obtained could contribute to a baseline for relevant research of transportation topological robustness.

1. Introduction

Many metropolises such as New York, Beijing, and Moscow have continually increased investments in construction of rail transit lines, resulting in complex subway systems that possess high station densities and intricate inter-station coupling relationships (Angeloudis and Fisk, 2006; Xu and Sui, 2007; Zhang et al., 2012). The applications of such high-capacity subway systems have considerably eased the urban traffic burden caused by the surge of populations. However, the frequent occurrence of random failures (RFs) has increased our awareness of the fact that unreasonable planning as well as insufficient collaborative management measures would impair the overall reliability of a subway system. In addition, malicious attacks (MAs) such as targeted destructions and retaliatory disruptions to the system components can impair the functionality of entire system, causing considerable socio-economic costs (Albert and Barabási, 2002; Lee et al., 2008; Newman et al., 2001; Sparrow, 1991; Wang, 2013; Zhou et al., 2014). Therefore, a better understanding of the topological characteristics of rail transit systems is crucial for improving the robustness of them against both inside disruptions and outside attacks (Crucitti et al., 2003; Derrible and Kennedy, 2010; Kyriakidis et al., 2012; Wu et al., 2008).

The increasing availability of data acquisition on large systems and the rapid development of artificial intelligence techniques aided by computer technology (Vernez and Vuille, 2009; Zhao et al., 2012; Zhong et al., 2010) have led to great advances in our understanding of the topological complexity of critical infrastructures (Ding et al., 2014; Glickman and Erkut, 2007; van der Vlies and van der Heijden, 2013; Zhang et al., 2014). In spite of the significance, the study of these critical infrastructures is an essentially complicated issue since they are continuously growing in complexity and heterogeneity, which makes a single modeling unreliable in this case. As a consequence, multiformalism techniques have been proposed and successfully applied to related works (Flammini et al., 2009b). These techniques have took into account multiple

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factors (e.g. occurrence probability of hazard, radiation intensity of hazard, equipment resilience and etc.) related to both intra and internal interactions among different infrastructures, contributing to models that are closer to reality (Bernardi et al., 2011; Sen et al., 2008). Furthermore, recent researches have incorporated quantitative methods to assess the risk of public services, aiming to provide more accurate management plans instead of conventional qualitative ones (Bajcar et al., 2014; Flammini et al., 2009a; Si et al., 2012). Therefore, we are able to conclude that the safety and security investigations in terms of critical infrastructures such as electricity networks, pipelines, and public transportation networks are not an easy issue. Deeper knowledge of the interaction relationships among sub-units in a complex network is thus requisite for an optimization of security system. As a result, _ENREF_16using complex network theory to study the robustness of subway system has become a hot topic in the field of safety management of rail transit systems, given its thorough consideration of the complex interactions relationship in a network. Latora and Marchiori (2002) conducted statistical analyses on the topological properties of the Boston Subway system and concluded that the system exhibited the general characteristics of a small-world network. By comparing 33 metro systems in this world, Derrible and Kennedy (2010) adopted network analysis methods to the transportation literature and offered one application to enhance the robustness of metros. Bruyelle et al. (2014) conducted case studies on the 7/7 London bombings and other subway incidents using common behavioral models and proposed enhancements to the robustness of subway systems.

Admittedly, the size of a subway system is really smaller than a truly complex network. Thus, certain deviations between the features of the Beijing subway system (BSS) and a truly scale-free network are inevitable. However, there are several reasons and advantages for applying complex network theory to investigate the BSS, which consist of the following points: (i) the similarity in evolution pattern. Generally, the evolution of a scale-free network is characterized by a self-organized pattern, which means the new nodes are prone to link to nodes with highest connections in the original network. According to the historical data, the BSS is following a scale-free evolution pattern on the basis of several critical stations (i.e., Xizhi Men station, Xi Dan station, and etc.) (http://en.wikipedia.org/wiki/Beijing_Subway, accessed: September 1, 2014); (ii) conventional applications of complex network to various infrastructures such as power grid networks, internets, pipelines, and aviation networks have proved that the complex network theory, which was summarized from large scale networks, had a potential to be introduced to networks in different scales (Zhang et al., 2012); (iii) incidents occurring to the BSS recent years have demonstrated that when the accidents happened to hub stations, they often resulted in severe dysfunctions and traffic congestions of the subway system. However, these happened to normal nodes generally caused moderate influence on a local region and would be quickly handled (http://en.wikipedia.org/wiki/Beijing_Subway#Accidents, accessed: April 1, 2015). These phenomena in reality implicitly demonstrated the BSS shared similar topological features with a scale-free network. Therefore, three similar attributes between the BSS and a scale-free network, aforementioned, provided us with a premise and strong motivation to explore the BSS from a complex network theory perspective.

Nevertheless, most relevant studies in this field were limited to the field of complex networks, which meant they considered each station as a simple node in graph theory. Few literatures have fully considered the specific circumstances and the inherent topological features of a station. Moreover, the lack of analyses and discussions on geographic elements, economic conditions and population factors would considerably influence the study of configuration and spatial correlation of subway networks, which would be raised up in the current study.

In summary, preliminary identifications of the critical components of network and simulations of the possible scenarios to various accidents are requisite for elevating the resilience of a subway network and for minimizing the aftermath of disruptions. As a consequence, we took advantage of complex network theory in the current study to grasp a sense of the robustness of the BSS, aiming to identify the generic topological features of the transit networks. Moreover, spatial analysis techniques of Geographical Information System (GIS) were applied to conduct quantitative analyses on the spatial influence of the large subway system.

2. Background

2.1. The Beijing Subway system

Beijing, the capital of China, is the nation's political, economic and cultural center with a total area of 16,410 km^2 and a registered population more than 21 million. Until May, 2014, the BSS has a total of 18 lines, 279 stations, 41 transfer stations and a mileage more than 544 km (Fig. 1), ranking it the second largest subway to Shanghai in the world (http://en.wikipedia.org/wiki/Beijing_Subway, accessed: September 1, 2014). The BSS supports the majority public transit of Beijing City (over 3.6 billion rides in 2013), making it the busiest subway system in the world. All these features make it an ideal sample to investigate the robustness of the subway transit system. Stations and lines data (including those under construction) were acquired from the Beijing Subway official website (http://www.bjsubway.com/, accessed: December 23, 2013). All data were first geo-referenced to WGS-84 coordinate system to ensure the accuracy of data registration.

2.2. The definition of various failures and attacks

A subway network system generally encounters two types of incidents, i.e., random failure (RF) and malicious attack (MA) (Kyriakidis et al., 2012; Wang et al., 2014; Wang, 2013). Common behaviors of these two were summarized to Table 1.

The occurrence of subway accidents can be attributed to a great many precursors, varying from a natural error to an anthropogenic attack (Lu et al., 2013; Wang and Fang, 2014). Due to the uncertainties of these precursors, it is extremely difficult to quantitatively specify the corresponding destructive power for each failure or attack. As a consequence, we specified a RF as the dysfunction of a network caused by failure on one or several nodes with a random probability, whereas a MA as a targeted destruction manipulated by outside artificial forces (Ghedini and Ribeiro, 2011; Zhang et al., 2012). The difference of these two scenarios involves two aspects: (1) the probability of a RF is equal among all stations while MAs generally happen to hub stations with high degree or centrality; (2) the destructive power of a random anomaly is insignificant compared with a MA that would degenerate the function of entire station or line for a long time.

It should be noted that natural disasters were not taken into account in the study because we fundamentally assumed that natural disasters, which were able to impact the underground subway network, generally meant devastating destruction on a whole transportation system. For instance, the 2011 floods in Southeast Queensland destroyed the whole transportation system, which could hardly be simulated by a few stations or lines. However, these natural factors would play an important role in the safety assessment of large-scale transportation system, such as shipping and aviation that are exposed to external circumstances frequently.