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Vulnerability assessment of urban rail transit based on multi-static weighted method in Beijing, China

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ABSTRACT

Rail transit network (RTN) has become the core of urban public transport system. Because RTN's topological structure has become complicated with its scale, the phenomenon of overload operation frequently appears at stations or lines, reducing the stability of RTN in operation. There is a need to identify the key stations and to analyze the vulnerability of RTN in depth.

This paper quantitatively analyzes statistical topology parameters of Beijing rail transit network (BRTN) based on complex network theory (CNT). The key stations are evaluated by different evaluation indicators, such as node degree, betweenness, and strength. Then, a model is proposed to analyze the cascading failures of weighted BRTN considering loading and redistribution of multi-static passenger flow based on coupled map lattices (CML).

Results show that when the external perturbation is larger, the time of all stations failure is earlier once the failure is triggered. Moreover, the perturbation threshold for the cascading failure of weighted BRTN is determined. Transfer regularities of the risk stations in BRTN are researched under different combinations of the topological coupling coefficients and the flow coupling coefficients. Under attack, the threshold of loop line damaged is smaller than a straight line. And, while attacking the loop line, the discrete degree of peak time and all station failure time are higher under different perturbations, meaning that failure is hard to control.

This study provides recommendations on developing strategies for RTN design and performance evaluation. Future studies will focus on the coordination of weighted complex public transit networks other than passenger flow redistribution within RTN.

1. Introduction

Urban rail transit has become the mainstream of public transportation in developing countries due to the fast speed, large capacity, and convenience. During the year 2015 in Beijing, 3.32 billion trips were made via urban rail transit (i.e., around 9.11 million trips per day), accounting for approximately 45% of the total trips from all kinds of transportation (Beijing Traffic Development Research Center, 2015). The popularity of urban rail transit also implies that the failure of rail transit network (RTN) may cause serious disaster. Therefore, studies on the vulnerability of RTN has significant implications on controlling station failures and taking emergency management for protecting RTN and improving operation stability.

In an RTN, natural disasters, outbursts of passenger flows, and terrorist activities may lead to disrupted operation of stations or a line and even cause the whole RTN paralyzed. In Beijing, for instance, on August 26th, 2005, fire hazard led to Metro Line 1 breakdown for nearly 50 min, creating severe congestion at the road traffic around the loop line subway (Xiao, 2005). On July 5th,

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2011, an upward escalator equipment accident on Metro Line 4 in Dongwuyuan stations led to a stampede and serious casualties (http://www.bbaqw.com/js/335.htm, accessed: Mar. 5, 2016). Moreover, on December 12th, 2015, a passenger falling track caused signal failures for Metro Line 1, making a significant number of passengers stand at the stations for nearly one hour (http://house.people.com.cn/n/2015/0212/c164220-26,555,719–2.html. accessed: Feb. 15, 2016). All of these operation failures show that the security and efficiency of RTN have become important issues. Hence, it is necessary to discern vulnerabilities (that easily lead to disrupted operation of stations or a line) and formulate corresponding coping strategies, which is very important to improve the safety level of rail transit network operation.

2. Literature review

The concepts, vulnerability, and robustness, are widely used to measure network performance (Mattsson and Jenelius, 2015). In transportation system, network vulnerability is defined as the sensitivity to the incidents that may result in a reduction in network serviceability. Correspondingly, robustness is referred as the capability to withstand unexpected incidents with an acceptable reduction in operating performance and is measured by the decrease of capacity and the efforts for disruption recovery (Berdica, 2002). The vulnerability is more about the sensitivity of a network; robustness concerns more with the response of a network. This study mainly focuses on the perspective of vulnerability for RTN.

The vulnerability of urban rail transit networks (URTN) has been investigated based on the graph and complex network theory (CNT) (Wang et al., 2008; Angeloudis and Fisk, 2006; Scott et al., 2006). Liu and Song (2010) analyzed the distribution of the network's degree, clustering coefficient, and average shortest path of Guangzhou rail transit. Zhang et al. (2011) measured the topological characteristics of the Shanghai metro system and evaluated the connectivity or reliability of metro lines. Wang (2008) constructed and the topological model of the BRTN and simulated the network efficiency under various attacks.

The reliability of URTN was researched by measuring the index of CNT and considering the global network. Chen (2010) presented that the URTN is rather robust to random attacks but is vulnerable to the largest degree node-based attacks and the highest betweenness node-based attacks. Derrible and Kennedy (2010) introduced robustness indicators and provided recommendations for improving the robustness of differently-sized metro networks throughout the world. Murray et al. (2008) proposed a basic typology of network vulnerability approaches, named scenario specific, strategy specific, simulation, and mathematical modeling.

While the aforementioned studies only considered the network topology issues, researchers recently began to take both network topology and passenger behaviors into consideration. Yang et al. (2015) proposed a new weighted composite index for evaluation of node importance and investigated the topological properties of metro systems through assessing metro network’s robustness in the face of random failures and malicious attacks. The topological analysis helps to protect metros from terrorist entry and assists the safety management of rail transit. Sun et al. (2015) introduced origin-destination (OD) flows into vulnerability investigation focusing on station vulnerability and proposed a station vulnerability evaluation model for identifying important stations within the metro network. And, it is identified that the urban rail transit network is rather robust to random attacks but is vulnerable to the largest degree node-based attacks and the highest betweenness node-based attacks. Rodríguez-Núñez and García-Palomares (2014) are interested in the importance of the links in a subway system. They assumed that link travel times and an OD travel demand matrix are known and that travelers choose the fastest route in the network to reach their destinations. Daniel Sun (2016) measured the metro network vulnerability from the perspective of line operation using field passenger traffic data, taking the Shanghai metro network as a case study.

As RTN is a dynamic network, its dynamic vulnerability is difficult to measure. Coupled map lattices (CML) method has been used to identify cascading failures (Kaneko, 1992; Zhang et al., 2015; Ren et al., 2015). Wang et al. (2006) discussed the global coupling network, scale-free network, and small world network of CML in cascading failure. Zhang and Zhang (2013) compared the cascading behavior of the RTN in Beijing, Shanghai, and Guangzhou based on the CML. Ma and Ma (2010a,b) put forward the cascading failure of directed network using CML and discussed the features of cascading failure in the tree network topology. Ma and Ma (2010a,b) analyzed the robustness of the different network topology based on CML. Chen et al. (2009) studied the sensitivity of network to the node degree and the spread of the cascading failure in the network under different attack strategy. Du et al. (2015) reformed a complex public transit network model with multi-links with CML and analyzed the cascading failures under the different external perturbations and coupling strengths.

There is no study on the vulnerability against random fault or intentional attack when considering passenger flow redistribution in the rail transit network. There is also need to identify the threshold to avoid cascading failures in URTN. This paper aims to conduct an in-depth analysis of the vulnerability of URTN to provide theoretical support for the planning and operation. The key stations are evaluated from the perspectives of the topology, flow redistribution, and route selection. Then, a model is proposed to analyze the cascading failures of weighted BRTN considering passenger-flow redistribution based on CML for improving operation security and stability of RTN.

3. Methodology

The importance of a link or node is determined not only by topology location in the network but also from the passenger flow rate it handles. Passenger flow is used as an essential element in RTN vulnerability studies. In this study, the procedure of vulnerability assessment of BRTN is described as Fig. 1. Topological structure model of BRTN is established in space L; the statistical topology parameters (such as degree distribution and average path length) are analyzed. The top primary stations of BRTN are identified based on the node degree, betweenness, and strength. Finally, the dynamic vulnerability of BRTN is studied using a cascading failure