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Measuring vulnerability of urban metro network from line operation perspective

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ABSTRACT

Urban metro systems are subject to recurring service disruption for various reasons, such as mechanical or electrical failure, adverse weather, or other accidents. In recent years, studies on metro networks have attracted increasing attention because the consequence of operational accidents is barely affordable. This study proposes to measure the metro network vulnerability from the perspective of line operation by taking the Shanghai metro network as a case study. As opposed to previous studies that focused largely on disruption of important nodes or links, this study investigates the disruption from the line operation perspective. Betweenness centrality (BC) and passenger betweenness centrality (PBC), number of missed trips, weighted average path length, and weighted global efficiency were analyzed considering relative disruption probability of each line. Passenger flow distribution and re-distribution were simulated for different disruption scenarios based on all-or-nothing assignment rule. The results indicate that the metro lines carrying a large number of passengers generally have a significant impact on the network vulnerability. The lines with circular topological form also have a significant influence on passenger flow re-distribution in case of a disruption. The results of this study provide suggestions on metro system administration for potential improvement of the performance of operation, and passengers may meanwhile have an improved alternate plan for their commute trip when a disruption occurs.

1. Introduction

Public transport networks are generally indispensable for mobility in urban areas, and metro networks are vital components of transit systems in major cities, acting as a key solution in supporting commuter traffic demand within metropolis area. In addition to huge capacity, metro systems also provide improved service experience such as punctuality and fast speed. The dependence on metro systems keeps growing in several cities over the world. According to the *Shanghai comprehensive traffic operation annual report, 2014*, 6.585 billion trips were made during the year in Shanghai, i.e., around 18.04 million trips per day, in which the Shanghai metro system accounts for approximately 43%, overtaking regular road transit for the first time. It also indicates that if the metro system fails, the consequence is serious and barely affordable. To guarantee efficient operation of a metro system, it is important to assess the vulnerability of the metro network to potential disruptions and identify lines whose incidents may have a crucial impact on both metro networks and travelers.

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Disruptions in a metro network may be caused not only by operational degradations of physical infrastructure, such as electrical failures and malfunctioning vehicles, but also from service degradations, including crew strikes, terrorist attacks, adverse weather, or other accidents (Cats and Jenelius, 2015). Taking Shanghai Metro as an example, on March 10, 2015, a train in Line 2 traveling in the direction towards Guanglan Rd. was forced to stop because of the sudden failure of a pantograph, causing loss of electrical power. The service disruption lasted for more than 5 h, affecting a large number of passengers.

Vulnerability and resilience are two widely used indices to measure network performance (Mattsson and Jenelius, 2015). Reggiani et al. (2015) reviewed recently emerging concepts of resilience and vulnerability in transportation. Network vulnerability in transportation system is defined as the susceptibility to incidents that may result in considerable reduction in network serviceability. In the context of metro network, resilience is correspondingly related to the ability to withstand unexpected incidents with acceptable reduction in operating performance, which is generally measured by the decrease of capacity and the efforts for disruption recovery (Berdica, 2002). Consequently, vulnerability is more about the susceptibility of a system and resilience concerns more with the response of a system. This study mainly focuses on the perspective of vulnerability for metro networks.

Extensive studies on network vulnerabilities have been carried out in many disciplines, while research on metro networks are mainly based on graph theory (Derrible and Kennedy, 2009, 2010a; Gattuso and Miriello, 2005). Gattuso and Miriello (2005) investigated the metro networks of 13 metropolitan areas using graphs and geographical indicators. Comparatively, Derrible and Kennedy (2009) studied the relationship between ridership and network design using updated graph theory concepts, concluding that the network topology plays a key role in attracting travelers to public transit. Various concepts of graph theory were used to describe characteristics of state, form, and structure using new or existing network indicators by studying 33 metro systems in the world (Derrible and Kennedy, 2010a).

Topology vulnerability of metro networks has drawn increasing attention in recent years (Deng et al., 2013; Yang et al., 2015). The topology characteristics and functional properties of the Nanjing metro network in the Jiangsu Province, China, were studied with the Space L model concluding that the network is robust against random attacks, but vulnerable to malicious attacks, similar to power networks (Chen et al., 2010) and air networks (Lordan et al., 2014; Janić, 2015). By investigating the 33 metro network systems throughout the world, Derrible and Kennedy (2010b) found that most metro networks were indeed scale-free (with scaling factors ranging from 2.10 to 5.52) and small-world networks. Two parameters, namely the functionality loss and connectivity of subway lines were used to measure transport functionality and connectivity by taking Lines 4 and 7 of the Shanghai metro, as examples (Zhang et al., 2011), in which the highest betweenness node-based attack was found, to cause the most serious damage to metro networks among the different attack protocols. These studies took important stations or links as disruption subjects to assess function loss of the network. However, no link or station is independent of others. Moreover, disruption of important links or nodes may result in operational failure of the entire line.

While the aforementioned studies only considered the network topology issues, researchers recently began incorporating passenger flow and travel cost to measure the metro vulnerability. Jenelius and Mattsson (2015) proposed to analyze the road network vulnerability, and the impact of disruption scenarios were evaluated from an economic point of view. Sun et al. (2015) introduced origin destination (OD) flows into vulnerability investigation focusing on station vulnerability and proposed a method for identifying important stations within the metro network. Rodríguez-Núñez and García-Palomares (2014) focused on link vulnerability by simulating targeted attack. Riding time and missed trips of disruption scenario were analyzed and results indicated that links carrying many trips and circular line played an important role in network vulnerability. Cats and Jenelius (2014) developed a dynamic and stochastic notion of public transport network vulnerability and found that the importance of links varied depending on the real-time-information provision schemes. Moreover, being devoid of standards in assessing disruption handling efficiency, effectiveness evaluation of a strategic capacity increase on alternative public-transport-network links was proposed to mitigate the impact of unexpected network disruptions (Cats and Jenelius, 2015). De-Los-Santos et al. (2012) evaluated passenger robustness in a rail transit network using time ratio as an evaluation index for two different cases: with and without bridging interruptions. Unfortunately, these studies generally ignored the overall performance of the network, although considerable attention was paid to the details of the reliability or vulnerability assessment.

Another branch of transport network analyses in recent years was on the recovery of disruption. Cadarso et al. (2013) proposed a two-step approach that combined an integrated optimization model (for the timetable and rolling stock) with a passenger behavior model for studying the disruption management problem of rail rapid transit networks. For this consideration, Kepaptsoglou and Karlaftis (2009) discussed the algorithms and models in bus bridging route designing to obtain good results. However, few studies deal with the riding duration and the number of missed trips. Thus, there is still a limitation in considering stations or links as a separate research subject.

Any type of service interruptions occurring on metro networks would affect daily normal functionality (Lou and Zhang, 2011). Previous vulnerability-related researches focus largely on passenger flow and travel time/distance. Unfortunately, little attention was paid from the perspective of line operation, which considers an entire metro line, rather than certain stations or links as an investigating subject during disruptions. In this study, a metro line with one non-operational line during a disruption is studied. The study intends to fill the gap from line operation perspective by taking actual passenger flow of a network into consideration, using the Shanghai metro network as a case study. The overall objective is to measure the