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Modeling network resilience of rail transit under operational incidents

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ABSTRACT

In the context of urban rail network analysis, most studies have focused on vulnerability analysis developing methodologies to measure consequences on network performance under destroy events. Few works are reported addressing the modeling of rail transit network resilience under operational incidents which could be more important analyzing the network performance changes under daily operations. This study demonstrates a resilience approach for rail transit network under daily operational incidents. Integrating the network topological and passenger volume characteristics, this approach explicitly accounts for the impacts of accumulative affected passengers quantifying the varying resilience of rail network with time under different incidents. The proposed methodology was applied to Shanghai Metro Network in Shanghai, China. Results show that critical stations are identified differently depending on duration time of different incidents and characteristics of the failed stations, and stations on network legs could be more important than those with redundant rail alternatives. Conclusions of this research would also have practical implications for the management and decision making of rail transit network under daily operational incidents.

1. Introduction

Consisting of rail and light rail, urban rail transit is playing an important role in people's daily travel. The importance of urban rail transit could be observed not only from the widely spread rail network all over cities but also from the large passenger flow it serves. Thus, urban rail transit network has to be reliable under regular operations and resilient under incidents. Incidents such as train breakdowns, electrical failures, and communication system breakdowns would result in delay and cancellation of thousands of trips as well as economic and opportunity losses (Cox et al., 2011). Consequently, there are growing research interests in the analyses of transportation network vulnerability and resilience investigating impacts and recovery of transportation systems under operational or disastrous incidents. Among these efforts, lots of attention has been attracted to road transportation network with well-established measures (Jenelius et al., 2006; Taylor et al., 2006; Chen et al., 2007; Lu and Peng, 2011; Oliveira et al., 2016). Different from road transportation, rail transit network could be more vulnerable but less resilient due to its fewer route alternatives and large number of people affected as well as associated risks such as passenger crowd trample under incidents. Rail transit system also includes interdependent electrical, communication, and rail facility systems, which contributes to high exposure and vulnerability to incidents and disruptions. However, according to Wang et al. (2014) and Mattsson and Jenelius (2015), urban rail transit receives less attention and relatively few works are reported on rail network vulnerability and resilience until recent years (Derrible and Kennedy, 2010; Rodríguez-Núñez and García-Palomares, 2014; Cats and Jenelius, 2015; Cats et al., 2016).

Analysis of rail transit network is predominately researched from the view point of vulnerability under incidents, which could be

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defined as the susceptibility to incidents that can result in considerable network serviceability reduction (Berdica, 2002). A large amount of literature studies rail transit network vulnerability based on complex network theory exploring the vulnerability of network topology if nodes or links of the network are failed. Degree, betweenness, centrality measures, and connectivity methods are usually used (Derrible and Kennedy, 2010; Zhang et al., 2015; Dimitrov and Ceder, 2016; López et al., 2017). This tradition of vulnerability analysis could be important for the planning and design of urban rail transit network. However, the topological vulnerability would address only the network topology characteristics under incidents ignoring impacts on travel characteristics such as passenger flow and travel time, especially considering the large amount of rail passengers (Mishra et al., 2012; Cats and Jenelius, 2015). As a result, another tradition of rail transit network vulnerability analysis called functional measure addressing impacts on passengers' travel has been addressed recently. Rodríguez-Núñez and García-Palomares (2014) developed a rail transit network vulnerability approach based on changes in travel time and trip distribution. The methodology is applied to the Madrid Rail system identifying critical links and lines. In an evaluation of the effectiveness of strategies reducing disruption impacts on transit network, Cats and Jenelius (2015) employ passenger utility measures to quantify network-wide consequences on rapid public transport networks of Stockholm, Sweden while integrating stochastic passenger supply and demand, dynamic route choice, and operation capacity limitations. Based on a travel-time-based passenger welfare function, Jenelius and Cats (2015) measure public transport network robustness and redundancy in a dynamic transportation model. Cats and Jenelius (2014) find that betweenness centrality itself may not be a good indicator of link importance after integrating betweenness centrality and dynamic costs of operators and passengers in their transit network vulnerability analysis. Two key indicators of average disruption delay time and total disruption delay time are used by Fikar et al. (2016) to evaluate the impacts of rail disruptions. These efforts contribute to a further development of measures addressing the consequence component of rail network vulnerability analysis. Recently, the probability or exposure component of rail transit network vulnerability analysis has been addressed by Cats et al. (2016) accounting for passengers' exposure to link failures by elaborating the frequency and duration time of possible disruption events in the Netherlands.

Based on recent reviews of Faturechi and Miller-Hooks (2015) and Mattsson and Jenelius (2015), less extensive literature on transportation system resilience than vulnerability analysis is found. Defined as the capability of a transportation system to recover rapidly from a severe shock to achieve its original state (Cox et al., 2011), however, the network resilience shares similar concept and methodology to the network vulnerability analysis. Methodologies addressing the resilience of rail transit network are also represented by topological measure and functional measure. Reggiani (2013) highlights the role of topological connectivity in the analysis of network resilience and outlines operational measures enhancing network resilience. Derrible and Kennedy (2010) interpret robustness more specifically as alternative paths and likelihood of accidents. Based on a functional measure, De-Los-Santos et al. (2012) measure passengers' resilience by comparing the combined travel time and passenger flow on each edge before and after rail failures on the Madrid rail transit network. D'Lima and Medda (2015) address the resilience of London Underground network from the diffusive effects of shocks on passengers. Miller-Hooks et al. (2012) agree that the resilience of transportation network should include both topological and operational ability to cope with disruptions. Zhang et al. (2015) argue a broad concept of network resilience accounting for not only the system's ability to absorb changes but also adaptive actions that can be taken to preserve or restore network performance. In a recent work, Cats et al. (2017) measure link criticality and degradation rapidity in a public transport network robustness model connecting local capacity reductions to network-wide performance changes.

It could be learnt from the above review that the majority of rail transit network analyses are situated in the vulnerability analysis focusing on methodology developments measuring consequences on network performance as shown by Stage 1 of the network performance curve in Fig. 1. Current vulnerability measures are mostly rooted in network topology and graph theory from the supply side neglecting impacts on rail passengers from the demand side. However, as indicated in Fig. 1, network performance curves under incidents change not only in Stage 1 but also in Stages 2 and 3, and network vulnerability analysis addresses only one part of the performance curves, and thus has rare implications for the other two stages which are important for the recovery of rail network. Moreover, network resilience analysis based on topological measures could hardly describe the recovery capability and rapidity of the

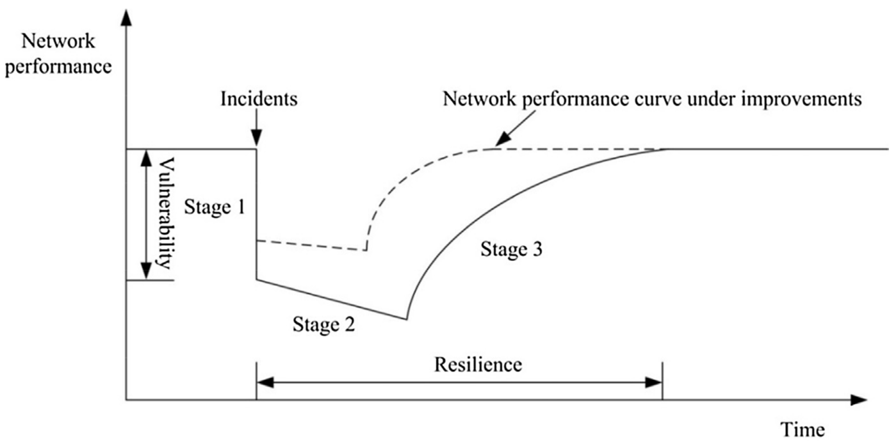

Fig. 1. Rail transit network performance curve under incidents.