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Resiliency assessment of urban rail transit networks: Shanghai metro as an example

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ABSTRACT

This paper presents a general framework to assess the resilience of large and complex metro networks by quantitatively analyzing its vulnerability and recovery rapidity within unifying metrics and models. The connectivity performance of network is indicated by the network efficiency. The resilience of a metro network can be associated to the network performance loss triangle over the relevant timeline from the occurrence of a random or intentional disruption to full recovery. The proposed resilience model is applied to the Shanghai metro network with its 303 stations and 350 links as an example. The quantitative vulnerability analysis shows that the Shanghai metro with its L-space type of topology has a strong robustness regarding connectivity under random disruption but severe vulnerability under intentional disruption. This result is typical for small-world and scale-free networks such as the Shanghai metro system, as can be shown by a basic topological analysis. Considering the case of one disrupted metro station, both the vulnerability and resilience of the network depend not only on the node degree of the disrupted station but also on its contribution to connectivity of the whole network. Analyzing the performance loss triangle and the associated cost from loss of operational income and repair measures, an appropriate recovery strategy in terms of the optimum recovery sequence of stations and the optimum duration can be identified in a structured manner, which is informative and helpful to decision makers.

1. Introduction

Urban rail transit systems (named subsequently as metro systems) offer an effective solution for addressing transportation problems in cities by significantly increasing the capacities of public transportation. This benefit has driven an expeditious development in the construction and operation of metro systems in many metropolitan cities. As the number of metro lines increases, metro systems often grow to a large and complex network scale. For example, Shanghai has a metro system with 303 stations and 350 tunnels over 617 km. Although a large-scale metro network makes public transportation attractive and convenient, any accident impacting this mega system would greatly affect not only the serviceability of this critical infrastructure but also the safety of passengers. For example, in September of 2011, a signal failure occurred in a station of metro line 10 in Shanghai, China. Two metro trains crashed in a tunnel due to the loss of signal causing 271 injured passengers and 30-h halt of the whole metro line (Mu, 2011). In view of these circumstances, the safety of metro networks is a key concern that requires an enhanced understanding of these networks through extensive research.

Quite a number of studies have been carried out by analyzing networks for the safety of metro systems in particular with the topographical mapping modelling (Crucitti et al., 2003; Derrible and Kennedy, 2010; Watts and Strogatz, 1998; Zhang et al., 2013; Zhang et al., 2011). Essentially, a metro network can be mapped into a topological graph with the simplification of metro tunnels and metro stations, respectively, as links and nodes used in topology (Zhang et al., 2013). Topological analysis, i.e., consisting of nodes and links, the path length and cluster coefficient of a network provides an effective and logical basis to characterize the safety of a transportation network (Derrible and Kennedy, 2010). Watts and Strogatz (1998) proposed a model termed *small-world network* for complex network analysis. The

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Nomenclature

Notations

G	topological vector for metro network
S	node set of a metro network
s_i	node in a metro network
N	node number in a metro network
E	link set of a metro network
e_{ij}	link between node s_i and s_j in a network
A	correlation matrix for a network
a_{ij}	correlation between node s_i and node s_j
d_{ij}	path length between node s_i and s_j
L	characteristic path length of a network
D	diameter of a network
C_i	clustering coefficient for a node in a network
C	clustering coefficient of a network
$P(k)$	distribution of node degree for a network
E_f	network efficiency
V	vulnerability of topological metro network
$Q(t)$	system performance of a metro network at time t
t_0	time moment when failure or attacks occur to the metro network
t_1	time moment when the metro network is fully recovered from a disruption
t_h	time duration from the disruption moment t_0 to the recovered moment t_1
R_e	resilience index for metro network
C_{total}	cost during the system disruption
$C_{\text{total, PV}}$	present value equal to the total cost at time of recovery
$C_{\text{disruption}}$	cost referred to the loss of system performance
C_{ticket}	cost referred to the income loss of metro ticket
Vol	passenger volume of the metro network
Vol_n	initial passenger volume of a metro network in normal condition
Vol_d	reduced passenger volume of a metro network after disruption
Vol_{Loss}	total loss of the passenger volume during the disruption
C_{repair}	cost related to the implementation of repair measures

small-world network system is typically highly clustered and yet have small characteristic path lengths, which conceptually shows a robust connectivity of the nodes for a network subjected to any disruption. Barabasi and Albert (1999) investigated large-scale networks and found that the node connectivity in those networks, i.e., network connectivity, often follows a scale-free power-law distribution. This result suggests that the connectivity of the network is robust under a random failure yet is vulnerable under an intentional attack.

The above network assessment models, however, are mainly qualitative with conceptualized measures that do not offer a rigorous comparison of safety levels among networks. In this respect, network analysis with quantitative measures of robustness and vulnerability is thus helpful for examining the safety level of a specific network. Albert et al. (2000) quantitatively analyzed the robustness of metro networks in the event of an accident. The robustness of a metro network here is expressed in terms of the residual network connectivity after the disruption of nodes in the network. Crucitti et al. (2004) also studied the robustness of two types of large-scale networks, i.e., a random network and scale-free network, for the performance of network connectivity. These two studies revealed that scale-free networks have a high robustness index under random attacks but a low robustness index under intentional attacks. Recently, a similar analysis of the robustness of metro networks was also reported by Zhang et al. (2011) and Yang et al. (2015). Additionally, disrupting a large-scale metro network by an accident affects not only the robustness but also the subsequent recovery. Recovery profiles over time greatly affect the economic and social wellbeing outcomes that are of great concern to metro owners. The rapid recovery of a network's connectivity from a disrupted state to the normal state is a key concern among engineers (Francis and Bekera, 2014). However, a robustness assessment focuses only on the network safety in the event of an accident without considering recovery. In the context of recovery, robustness and vulnerability analyses are still insufficient to offer a rational recovery strategy in terms of recovery sequencing and duration for stations and tunnels in a metro network.

A comprehensive safety assessment model includes both the network robustness and the recovery profile as provided by Ayyub (2014). In this context, the concept of "*resilience*" would provide an appropriate solution to cover both the robustness and recovery in a single model for safety evaluation of a network system (Ayyub, 2015; Bruneau et al., 2003). Resilience, according to U. S. Presidential Policy Directive (PPD-21, 2013), means "*the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.*" Fundamentally, the resilience of a system is often quantified by relating it to a resilience loss triangle represented by the difference between a normal performance evolution curve and a disrupted performance curve along with the time duration of disruption and recovery stage (Frangopol and Soliman, 2015). A resilient system can be quantitatively defined by the system with a minimized performance loss triangle, also termed resilience loss triangle. The optimized recovery sequences and duration necessary to minimize the resilience triangle thus offer a basis for defining recovery strategies after disruptions (Zhang and Wang, 2016).

The concept of resilience as used herein was initially and formally introduced by Holling (1973) for ecologic systems. Later on, a broader interest in resilience was triggered by the 2001 World Trade Center attack in the United States. Typical uses of resilience analysis has covered mostly water resource systems (Hashimoto et al., 1982), power networks (Henry and Ramirez-Marquez, 2012) and the seismic hazards for bridges (Dong and Frangopol, 2015). Resilience analysis for urban rail transit systems, however, has been quite limited. On the other hand, resilience analysis is of great necessity and importance in order to identify optimized recovery sequences after network disruptions. One might realize that a metro network, to some degree, is similar to the power network but with a different topological space of nodes and links and a different recovery philosophy in terms of sequence and timing. These similarities can be exploited in the development of respective approaches. In addition, the current practice of recovery is purely based on empirical judgement without a rational model to obtain an optimum repair duration and costs during the recovery stage (Huang and Zhang, 2016; Zhang et al., 2018).

This paper provides a general framework for the resilience analysis of large-scale metro network systems that offers an immediate basis for identifying both the best recovery sequences to minimize the performance loss and the best repair duration to minimize the costs associated with disruption and recovery. The performance of a metro network in this paper refers to the connectivity of stations in an integrated metro network (hereafter termed network connectivity). The development of this framework requires the introduction of several concepts and models in the context of metro networks as follows:

1. Basic mapping of a metro network into a topological graph;
2. Defining and measuring vulnerability and robustness of the topological metro network;
3. Developing resiliency metrics based on the topological metro network;
4. Accounting for costs during the disruption and recovery stage.