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# A new approach to understand metro operation safety by exploring metro operation hazard network (MOHN)

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ABSTRACT

Numerous metro accidents expose the vulnerability of metro system. As cities are rapidly building and expanding metro systems, it is essential to thoroughly explore the nature of metro operation safety. Metro accidents can be regarded as an emergent property that arises from the unusual interactions of system components. These interactions could give rise to the phenomenon that several interrelated hazards simultaneously emerge in one single accident. Understanding these interrelations among hazards is indispensable to study metro operation safety. From this standpoint, 28 hazards and 48 interrelations among hazards were identified from 134 accidents and expert interviews, which were the foundation of establishing metro operation hazard network (MOHN). Whereby complex network theory, seven parameters were applied to further reveal the structural properties of MOHN. The results indicate that the MOHN is a scale-free network for the cumulative degree distribution obeys power-law distribution. The scale-free property of MOHN is indicative of its robustness to random attacks and its vulnerability to deliberate attacks. Nichetargeting controlling hazards of high degrees and betweenness centrality can significantly decrease the metro operation risks. Moreover, MOHN also possesses the small-world property for having a relatively high clustering coefficient and small shortest path length. This indicates that risks would be transmitted very quickly in MOHN. Secondary and derivative hazards should receive enough attention for the rapid propagation of MOHN. Revealing the inherent properties of MOHN assist in making beforehand strategies prior to metro accident and contributes to elevate system safety of metro operation.



## 1. Introduction

The increasing congestion and worsening pollution in many of today's developing cities are relatively recent phenomena, having paralleled the rapid economic growth of those cities. China is no exception especially with regard to its accelerated urbanization process (Ma et al., 2007). According to a survey implemented by Peking University's National Development Research Institute, Beijing suffers $11.3 billion (or 3.6% of the Beijing's GDP) loss from traffic congestion annually, which is much higher than the estimated value (approximate 1–3% loss in GDP) conducted by the World Bank (Gwilliam, 2002). Not only people's daily lives have been restricted by nerve-wracking traffic congestion, but also the sustainable development of society and economy (Kong et al., 2016).

As a modern means of transport advantageous with large transportation capacity, high speed, low pollution, energy saving and comfort, Metro is the ideal choice to relieve these problems and has quickly been adopted by local governments all around the world. With stepping up investment in infrastructure, Chinese urban metro system undergoes rapid expansion during last decades. By the end of 2014, 22 cities already have operating metro systems, with approximately 35 million passenger trips being made on a daily trip (Yearbook, 2015). Along with the extension of metro routes, the percentage of metro passengers in total public passengers is increasing, which are present in Fig. 1. This statistical data indicates that metro has evolved into the backbone of public transportation system and become the primary means of transport for residents' daily commute.

However, during the expansion process of urban metro system, catastrophic accidents have occasionally occurred, for instance, Daegu metro fire killed at least 198 people and injured at least

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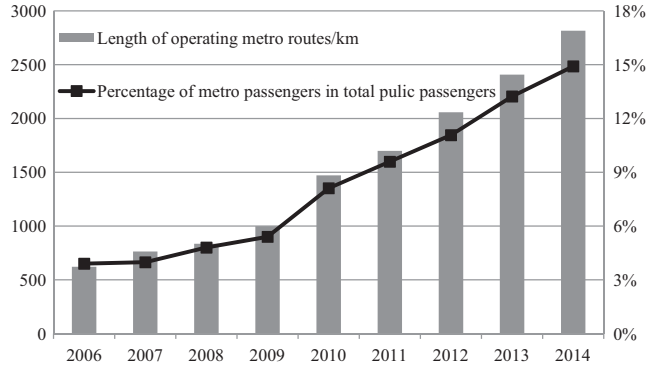


**Fig. 1.** The scale of metro system in China.

147 on February 18, 2003 (Shi et al., 2012), and Washington metro train collision of June 22, 2009 killed 9 people and injured approximately 80 (Murray-Tuite et al., 2014), just to name a few. Such metro operation accidents not only caused huge economic losses, including loss of life and property, but ignited public debate about the safety of metro system. More than providing fast and convenient services, metro system is preferred to be a safe and reliable transportation mode. Consequently, safety analysis of metro operation, which has been proved to have significant contributions to improve systems' performance (Rausand, 2011), has raised a lot of attentions recently.

In industrial safety research, there is a growing consensus among safety professionals and researchers that accidents are not usually caused by a single failure or mistake, but by the confluence of a whole series, or chain, of errors and hazards (Ai et al., 2014). Due to metros' operational characteristics of multi-disciplinary collaboration, and exogenous and endogenous functional dependencies and interdependencies (Deng et al., 2015), this phenomenon also existed in metro accidents which results in several hazards concurrently emerge in one accident. Moreover, a hazard could be the trigger of another hazard and hazards are mutual interacted due to the space limitation or operational characteristics of metro system. These interactions among hazards form a metro operational hazard network (MOHN) which poses a large issue for the safety operation of metro system. Hence, capturing the complexity of MOHN is essential and beneficial to improve safety performance of metro operation. In such context, this paper aims to implement a comprehensive analysis of interactions among hazards in metro system. Such analysis process will be carried out on foundation of the databases including plenty of metro accidents records and expert interviews in metro company. After extracting the interrelations among hazards from the database, MOHN is formed and the topological characteristics of MOHN are analyzed by utilizing complex network theory. The remainder of this paper is organized as follows. Section 2 makes a literature review about the safety analysis of metro system in general and discusses the drawback of current research. An analytical framework and the process of forming MOHN are presented in Section 3. Section 4 utilizes the complex network theory to explore the statistical properties of MOHN. Based on the result from Section 4, system improvement strategies are compared and the drawbacks of current research are discussed in Section 5. Finally, the conclusions are summarized in Section 6.

## 2. Literature review

Metro systems provide essential transport services which enable our society to function in contemporary era. With the purpose of improving the performance of metro systems, plenty of researches into safety analysis about metro operation have been conducted during last decades. Lu et al. (2012) constructed a safety risk framework, which integrated the technical system risk models and social and structural aspects of safety prediction models to track the paths of influence starting form root organizational factors to the accidents. Yan et al. (2012) established a Data Envelopment Analysis (DEA) based model to access the risk of crushing and trampling accident in subway station. Sari et al. (2012) proposed a multi-criteria evaluation system of the urban rail systems in Istanbul to assist in making the priority assignment of the scarce resources. Similarly, Marzouk and Aty (2012) developed a system using BIM technology for priorities of objectives and budget allocation in metro infrastructure rehabilitation. Kyriakidis et al. (2012a) presented a new safety maturity model and safety maturity index for addressing the behavioral and attitudinal culture, technical and operational elements, and actual achievements in terms of safety outcomes. Kyriakidis et al. (2012b) also proposed the human performance railway index operational index (HuPeROI) to estimate the human error probability in metro operation and formulate mitigation strategies to minimize operators' degraded performance phenomena. Lu et al. (2013) utilized Case-Based Reasoning (CBR), incorporating case representation and retrieval, to automatically recognize the safety risk and safety measures of metro operation cases. Song and Li (2014) probed into the relationship between the passenger density and the safety level of the station platform. L. Wang et al. (2015) put forth an integer programming model for passenger flow control based on the analysis of passenger delay and the processes by which passengers alight and board to ensure passengers' safety. Other safety-related studies are concerned with the topological structure of the metro network. Latora and Marchiori (2002) defined measures of local and global network efficiencies for the Boston subway system and found that small-world behaviors existed in that system. Seaton and Hackett (2004) also discovered the small-world property in the Boston and Vienna rail systems, and further draw comparisons between them on their different train-line architecture. Derrible and Kennedy (2010) explored the complexity of 30 metro systems and discussed the impacts of the topological features on the robustness of metro systems. Sun et al. (2015) proposed a vulnerability evaluation model to analyze the network and station vulnerabilities of the urban rail transit system based on complex network and graph theories. Yang et al. (2015) investigated the topological properties of metro systems and assessed metro network's robustness in face of random failures and malicious attacks to better assist the safety management of rail transit. These topological analysis studies are issues of great operational importance to protect metros from terrorist entry. Additionally, emergency evacuation is a contributing factor in keeping the minimized damage and avoiding loss of life after hazards break out. Researches in this area are also considerable parts in safety analysis of metro operation. Zhong et al. (2008) developed an occupants evacuation dynamic model based on Code for design of metro to simulate passengers evacuation process from deep buried metro station. Jiang et al. (2010) focused on how maximum upstairs speed and the average minimum width affected the evacuation through the staircase and explored the possible causes on the differences to affect the effect of varying the two parameters. Tsukahara et al. (2011) computed different evacuation routes in the case of a large-scale subway fire and concluded that downward evacuation was more effective under such situation Shi et al. (2012) analyzed the safety strategy of evacuation and used an agent-based model to simulate the evacuation processes in different fire cases.

Risk assessment is also an important aspect in safety analysis studies in which probabilistic risk assessment (PRA) originated in U.S. aerospace programs and widely applied in the nuclear industry is the most fundamental tool. In metro system, PRA is employed