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A station-based rail transit network vulnerability measure considering land use dependency

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ABSTRACT

Natural disasters, intentional attacks, and operational incidents are posing increasing threats on rail transit network. The vulnerability of rail transit network becomes an important concern of researchers and rail managers. This paper proposes a station-based accessibility approach addressing passenger flow and land use characteristics in rail transit network vulnerability analysis. Land use variables are measured as the independency degree on rail transit. The reduction ratio of network accessibility before and after incidents is calculated to measure the potential consequences. Based on results of comparisons with existing methods with the help of an example problem, the proposed accessibility measure demonstrates better and more reasonable results as not only the rail network and passenger flow but also the land use and travel alternative variables interacting with rail transit are accounted. The proposed method is then applied to Shanghai metro network. The data for analysis include rail transit network data, passenger flow data, and land use data around stations. Results indicate that the vulnerability of rail transit network is jointly affected by its network topology, passenger flow, and land use variables. Unbalanced land use, high plot ratio, and the less travel alternatives will increase the dependency of land on rail transit travel, leading to high network vulnerability once disrupted. Results of this work will inform rail transit managers of the degree of network vulnerability and critical stations and links as well as the land use dependency on vulnerability. Findings of this study may have implications not only for the planning of other transit modes to enhance the resilience of public transit network in vulnerable areas but also for the land use development around rail stations.

1. Introduction

Rail transit has been developing rapidly and become an increasingly important mode of people's intracity travel, especially in developing countries such as China. It is expected to be more than 45 cities in China providing rail transit service by 2020. Rail transit passengers are increasing overwhelmingly in these cities, for example, the peak day passengers both in Beijing and Shanghai reached over 10 million in 2016. The huge passengers and huge rail transit systems make rail network vulnerable to natural disasters, intentional attacks, and operational incidents. Meanwhile, with the rapid urban sprawl and the advocacy of transit oriented development (TOD) around rail transit stations in developing countries, there are unbalanced and/or over development of land use around rail transit stations, which makes land use along rail lines highly dependent on rail transit travel. This high dependency is posing potential threats on people's daily travel if rail stations or links are disrupted or closed.

Considering the serious impacts and large amount of passengers affected, many research efforts have been devoted to rail transit network vulnerability analysis, evaluating the vulnerability of rail transit network and identifying critical stations, links, or regions under incidents on network. In terms of transport network vulnerability analysis, there are already well developed methodologies measuring the performance of transport networks under incidents (Jenelius et al., 2006; Taylor et al., 2006; Burgholzer et al., 2013; Chen et al., 2015; Dimitrov and Ceder, 2016). The vulnerability of rail transit is initially researched based on complex network theory which addresses the physical structure of rail network (Derrible and Kennedy, 2009; Yang et al., 2015; Dimitrov and Ceder, 2016). However, the pure network structural vulnerability could not reveal the changes in passenger flow characteristics such as OD distribution and travel time under incidents, as the consequence of an incident event is usually evaluated from the number of people affected and the extent of these effects such as travel distance/time changes. As a result, there are growing research interests in rail transit network vulnerability analysis addressing passengers' travel time and travel distance changes under incidents (Criado et al.,

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2007; Rodríguez-Núñez and García-Palomares, 2014). Unlike other transportation modes, rail transit is more interdependent on land use around stations resulting from either the TOD or people's preference on rail transit travel. Besides the network topology and passenger flow, rail transit network vulnerability may be also affected by land use variables interacting with it. For example, passengers living around suburban stations dominated by residential land use with less other travel alternatives depend much more on rail transit, and thus are more vulnerable under rail incidents. Previous vulnerability studies address mainly on rail transit system itself, i.e. network topology and passenger flow, and regard land use the same throughout all stations, neglecting the differences in land use which has different dependencies on rail travel. As a result, this paper aims to evaluate the vulnerability of rail transit network with land use factors around stations and passenger flow characteristics, and identify the land use impacts on rail transit network vulnerability.

The remainder of this paper is organized as follows. Section 2 reviews literatures on transport network vulnerability analysis, particularly for rail transit network. The methodology measuring rail transit network vulnerability is proposed in Section 3. Section 4 illustrates an example problem to compare the proposed methodology with existing measures. Section 5 demonstrates an application of the methodology in Shanghai rail transit network with results and discussions provided in Section 6. Section 7 concludes this study.

2. Literature review

The majority researches on transportation network vulnerability have been focused on road network (Wang et al., 2014). Berdica (2002) presented the concept and framework of transportation vulnerability analysis, however, without methodological development of vulnerability measurement. One common analysis of road network vulnerability was based on network topology (Hu et al., 2009; Duan and Lu, 2014). Another widely used method was accessibility-based measure (Bhat et al., 2002; Kwan et al., 2003; Lu and Peng, 2011). Chen et al. (2015) developed a complete accessibility index considering different travel modes to measure the vulnerability of transport network under flooding disasters. Other measures included the importance-exposure method, game theory, travel time, and so on (Jenelius et al., 2006; Scott et al., 2006; Bell et al., 2008).

Rail transit network vulnerability has received less attention in the literature, and based on Wang et al. (2014), only 6% of related researches in transportation network vulnerability analysis addressed rail transit. The network-topology-based method was dominating the rail transit network vulnerability literature which was further addressed with degree centrality, betweenness centrality, network connectivity, and so on (Lam and Schuler, 1982; Derrible and Kennedy, 2009; Park and Gang, 2010; Mishra et al., 2012). Cats and Jenelius (2012) extended the betweenness centrality measure to a dynamic and stochastic network, and applied it to the rapid public transport system in Stockholm, Sweden to identify candidate important links. Based on the number of cycles in a network, Derrible and Kennedy (2010) proposed a robustness indicator to analyze thirty three rail transit systems worldwide to identify system stability under incidents. Besides network topology, other methods were also proposed and applied to rail transit network vulnerability. Rodríguez-Núñez and García-Palomares (2014) proposed a vulnerability methodology considering the changes of average travel time rather than physical network characteristics evaluating the rail transit network of Madrid, Spain. However, a limitation of this method was that it only measured the variations of average travel time ignoring the passenger flow distribution, which was insufficient to capture the impacts of rail incidents on passengers. Integrating passenger volume and travel time, accessibility has already been used as a system performance measurement for transportation network vulnerability under incidents. There are various forms of accessibility index depending on the purposes. Hansen integral accessibility index was used as an index measuring highway network vulnerability by Taylor and D'Este (2007). Afterwards, it was improved by Lu and Peng (2011) who took passenger flow into consideration emphasizing the importance and attractiveness of zones under flooding impacts. Another improvement of Hansen integral accessibility index was proposed by Sohn (2006) who considered two population-weighted impedance factors, i.e. distance and traffic volume. Chen et al. (2007) defined accessibility from a different perspective analyzing the vulnerability of transport network, and developed the hierarchic utility-based accessibility index for different levels based on combined travel demand model. Accessibility-based method could also be found in literatures on public transport network analysis (Chen et al., 2016; Nassir et al., 2016; Saghapour et al., 2016). Chen et al. (2016) defined an area public transport accessibility index and applied it to evaluate the accessibility values of traffic zones in Beijing. The proposed index could generate quantitative results for public transport network optimization. Incorporating all available paths and mode alternatives, Nassir et al. (2016) developed a utility-based travel impedance measure for public transport network accessibility capturing passengers' behavior and subjective perceptions of impedance. As a result, the development of accessibility measures in transportation network vulnerability analysis in general, and the study of public transport network analysis in particular, has become an important direction of research which has recently attracted a lot of attention.

The public transport network performance depends not only on its network topology, passenger flow, and accessibility but also land use around stations. As argued by Li et al. (2016), land use influences people's travel behavior to a certain extent and should be considered in transportation analysis as one of the most significant factors. It is critical to understand the interrelations between urban transit stations and different combinations of land use patterns with the ever-increasing TOD applications, in which differently combined land use patterns are usually indicated by the mixed land use degree index (Bhat and Guo, 2007). Land use characteristics impose specific spatial constraints for most, although not all, activities, and it has been used to build kinds of travel demand models. However, the impacts are bidirectional, and the demand for transport will also influence the features of land use such as the price of land, distribution of various kinds of service facilities (Hu et al., 2016). It can be reached that land use should be accounted when evaluating the performance of rail transit network such as vulnerability. As pointed by Litman (2016) that land use could be an important factor for the improvement of the accessibility index. Unfortunately, land use variables have not been found in previous literatures quantifying rail transit network vulnerability.

Rail transit network could be more vulnerable under incidents because of its low network redundancy but large daily passenger flow especially in populated countries. However, based on the reviews above, vulnerability analysis of rail transit network is still limited and mainly applied in developed countries with relative less population and developed land use around stations. Due to the obvious interdependency between rail transit and land use, land use characteristics could affect the performance of rail transit and should be included in the analysis of rail network vulnerability.

3. Methodology

Therefore, this study proposes a station-based accessibility index for rail transit network vulnerability analysis while including land use characteristics around stations. Based on the Hansen integral accessibility index (Taylor and D'Este, 2007), the importance of each rail transit station and the independency of land use on rail transit network are both accounted for the improvement of the accessibility index. The proposed accessibility index, called improved accessibility index, is aimed to measure the station accessibility under incidents, and it is defined as the potential opportunities for interaction among stations, in which the opportunities are weighted by the land use characteristics