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# Comparisons of complex network based models and real train flow model to analyze Chinese railway vulnerability

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## ABSTRACT

Recently numerous studies have applied complex network based models to study the performance and vulnerability of infrastructure systems under various types of attacks and hazards. But how effective are these models to capture their real performance response is still a question worthy of research. Taking the Chinese railway system as an example, this paper selects three typical complex network based models, including purely topological model (PTM), purely shortest path model (PSPM), and weight (link length) based shortest path model (WBSPM), to analyze railway accessibility and flow-based vulnerability and compare their results with those from the real train flow model (RTFM). The results show that the WBSPM can produce the train routines with 83% stations and 77% railway links identical to the real routines and can approach the RTFM the best for railway vulnerability under both single and multiple component failures. The correlation coefficient for accessibility vulnerability from WBSPM and RTFM under single station failures is 0.96 while it is 0.92 for flow-based vulnerability; under multiple station failures, where each station has the same failure probability *fp*, the WBSPM can produce almost identical vulnerability results with those from the RTFM under almost all failures scenarios when *fp* is larger than 0.62 for accessibility vulnerability and 0.86 for flow-based vulnerability.

## 1. Introduction

The economy of a nation and the well-being of its citizens depend on the continuous and reliable functioning of infrastructure systems, such as telecommunication systems, electric power systems, gas and oil systems, water supply systems, transportation systems, and so on. However, these systems are subjected to the following issues, such as unavoidability of damage due to natural hazards, cascading failures due to their interdependencies, component aging, demand increase, climatic change, terrorist attacks, which increase their vulnerabilities. Regarding the definitions of vulnerability, they vary by discipline and application [1–5]. For example, Haimes, a scholar in the system and information engineering field, defined vulnerability as the manifestation of the inherent states of the system (e.g., physical, technical, organizational, cultural) that can be exploited to adversely affect (cause harm or damage to) that system [1]. Aven, a professor in the risk management research field, defined vulnerability as the uncertainty about and severity of the consequences of the activity given the occurrence of the initiate event [2]. Considering these available definitions in the engineering field and to differentiate with other pertinent terms, such as risk and resilience [1,2], the authors simply define the vulnerability as the performance drop of an infrastructure system under a given disruptive event. Note that the performance can be measured by different metrics, which correspond to various vulnerability values. To better protect infrastructure systems, many scholars recently have applied the complex-network based models to describe infrastructure topologies and then study their vulnerabilities from a topological perspective. These models can be simply grouped into two types, depending on whether the "flow" upon infrastructure systems is considered or not.

The first type is the purely topological models, which describe infrastructure systems as networks, with system components represented as nodes and component relationships as edges, and then study the performance response of the networks under disruptive events without the consideration of particle transportation. Empirical studies show that some infrastructure topologies have exponential degree distributions and are robust to the failures of both randomly selected nodes and the most connected nodes, such as Chinese bus-transport systems [6], Indian railway system [7], urban street networks [8], North American power grid [9] and southern California power grid [10], water distribution networks in the United Kingdom [11], while some infrastructure topologies have power-law degree distributions and are robust to

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the failures of randomly selected nodes but very vulnerable to the failures of the most connected nodes, such as Indian airline network [12] and USA airline network [13], worldwide cargo ship network [14,15], internet [16], power grid of the western United States [10], eastern interconnected and western system electric transmission networks [17]. Besides the random failures and target attacks, many scholars have studied the vulnerability of infrastructure systems under other hazards by using topology-based approach, such as the seismic vulnerability of interdependent power, gas and water systems in Europe [18] and Shelby County, Tennessee, USA [19,20], the terrorism vulnerability of interdependent power, water, steam supply and natural gas systems in Massachusetts Institute of Technology (MIT) campus [21], the hurricane vulnerability of interdependent power, water and gas systems in Harris County, Texas, USA [22].

The second type is the artificial flow based models, which are based on purely topological models and further consider the dynamics of particles of interest over physical infrastructures. Modeling the real particle flow requires modeling the engineering properties of infrastructure systems as well as a huge amount of detailed data on their components, such as generator productions, load levels, line impedances in power grids, which are sometimes difficult to obtain due to security concerns. To overcome this problem, the artificial flow models assume particles move along virtual routes to capture the flow transportation and possible redistribution in real infrastructure systems. Some studies assumed the particles run along the shortest path between a pair of vertices, and then used betweenness as a proxy for the amount of particle passing through a vertex or an edge, where betweenness is computed as the number of shortest paths that pass through every component when connecting vertices. A disruptive event can cause some component failures and alter the infrastructure topology. Depending on the operation mechanisms of the infrastructures under consideration, some studies did not consider the flow or load redistribution, such as the railway systems to be considered in this paper, while some studies assumed that the altered infrastructure topologies further change all components' betweenness and cause some other components overloaded and failed until all remaining components' betweenness (load) less than their own capacities. This type of models have been used to study the vulnerability of western U.S. power transmission grid [23], North American power grid [24], Italian power grid [25], trans-European gas networks [26], transportation networks [27], and the seismic and lightning vulnerability of IEEE 118 power grid [28], the hurricane vulnerability of several power grids in Texas, USA [29,30], and so on.

For the above two types of models, they both overlooked the engineering properties of infrastructure systems, and then the vulnerability analysis results from these two models could be far from the results from the real flow models. Some scholars have analyzed the differences between the complex-network based models and the real flow models in power grids. For the Italian high-voltage power grid, the critical components identified from the purely topological model do not affect the functioning of the network after their removal when considering the real power flow [31]. However, under some conditions, some studies on power grids showed that the complex network based models can produce almost identical vulnerability results as those from the real flow model [32], which can provide decision makers suggestions to select an efficient model for rapid response to disaster preparation and restoration in some special scenarios. For other types of infrastructure systems, such as railway systems, they have different flow mechanisms, whether similar results can be found as those in power grids and how effective are the complex network based models to analyze railway vulnerability is worthy of research. This paper takes Chinese railway system as an example to show how effectively the complex network based models can produce the vulnerability results as those from the real train flow model.

The rest of this paper is organized as follows: Section 2 introduces the Chinese railway system and its network-based representation. Section 3 introduces a real train flow model and three typical complex network based railway models, including purely topological model, purely shortest path model and weight based shortest path model for railway vulnerability analysis. Section 4 analyzes and compares the Chinese railway vulnerability results from different models. Section 5 discusses the findings and provides conclusions and directions for future research.

## 2. Representation of Chinese railway system

The Chinese railway system plays a crucial role in the economy of China and the wellbeing of its citizens. In 2012, it transported around 1.89 billion passengers and approximately 3.89 billion metric tons of cargos. This system has approximately 2940 stations in total. This paper picks out important stations in China on a coarse-grained level according to the recent handy book "Chinese Railway Passenger Train Timetable" published in 2010 [33] and combines multiple stations in a city to one station for simplification. Finally, the coarse-grained railway system has $N=399$ stations, which are connected together by $E=500$ railway links. A geographical representation of Chinese railway layout is shown in Fig. 1.

Upon the physical layout, on a typical weekday there are 4196 trains running on the railway to transport passengers between different cities. These trains have eight types: high-speed trains, inter-city trains, bullet trains, non-stop or few-stop trains, express trains, fast trains, normal fast trains, normal slow trains, which are denoted, respectively, by type "G", "C", "D", "Z", "T", "K", "P", and "M". The number and the average speed of each type of trains are shown in Table 1. The initially departure and finally arrival stations as well as the detailed routines of each train can be also obtained from the handy book.

Based on the railway physical layout as well as all train routines, it can construct different railway networks, where nodes represent train stations, but edges can be interpreted differently, depending on the "spaces" under consideration. Kurant and Thiran introduced very clearly three "spaces" [27]: space of stations, where two stations are connected only if they are physically directly connected with no station in between; space of stops, where two stations are connected if they are two consecutive stops on a route of at least one train; space of changes, where two stations are considered to be connected by a link when there is at least one train that stops at both stations. Under different spaces, this paper constructs different Chinese railway networks with their topological properties, including average degree, diameter,

**Fig. 1.** A geographical representation of Chinese railway system.