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Assessing the role of network topology in transportation network resilience

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ABSTRACT

The abstract representation of a transportation system as a network of nodes and interconnecting links, whether that system involves roadways, railways, sea links, airspace, or intermodal combinations, defines a network topology. Among the most common in the context of transportation systems are the grid, ring, hub-and-spoke, complete, scale-free and small-world networks. This paper investigates the role of network topology, and the topology's characteristics, in a transportation system's ability to cope with disaster. Specifically, the paper hypothesizes that the topological attributes of a transportation system significantly affect its resilience to disaster events. Resilience accounts for not only the innate ability of the system to absorb externally induced changes, but also cost-effective and efficient, adaptive actions that can be taken to preserve or restore performance post-event. Comprehensive and systematically designed numerical experiments were conducted on 17 network structures with some relation to transportation system layout. Resilience of these network structures in terms of throughput, connectivity or compactness was quantified. Resilience is considered with and without the benefits of preparedness and recovery actions. The impact of component-level damage on system resilience is also investigated. A comprehensive, systematic analysis of results from these experiments provides a basis for the characterization of highly resilient network topologies and conversely identification of network attributes that might lead to poorly performing systems.

1. Introduction

The abstract representation of a transportation system as a network of nodes and interconnecting links, whether that system involves roadways, railways, sea links, airspace, or intermodal combinations, defines a network topology. Such topologies may have regular or irregular shape, and many topologies have been generically categorized. Among the most common in the context of transportation systems are the grid, ring, hub-and-spoke, complete, scale-free and small-world networks. Many arterial roadway networks have a grid or ring shape, networks of towns can be well-represented by small-world networks, while air systems are commonly shaped as hub-and-spoke networks. These networks can be characterized by various measures, and even networks with different topologies can have common characteristics. This paper investigates the role of network topology, and the topology's characteristics, in a transportation system's ability to cope with disaster. Specifically, the paper hypothesizes that the topological attributes of a transportation system significantly affect its resilience to disaster events. The impact of component (or local) damage on system performance is also investigated.

In this study, a definition of resilience given in Miller-Hooks et al. (2012) is adapted that explicitly considers the system's coping capacity, along with the effects of pre-disaster preparedness and adaptive response actions that can be quickly taken in the disaster's aftermath while adhering to a fixed, small budget and short duration of time for implementing recovery options. The system's coping capacity is measured through its capability to resist and absorb disaster impact through redundancies, excess capacities. The concept of resilience differs from that of similar, more commonly employed performance measures, such as vulnerability, in that resilience accounts for not only the ability of the network to cope with a disruptive event, but the impact of adaptive actions that can be taken to ameliorate damage impact.

Insights gleaned from results of systematically designed numerical experiments on 17 generic network structures provide a basis for the characterization of highly resilient network topologies and conversely identification of network attributes that might lead to poorly performing systems. In the assessment, three resilience measures based on throughput, connectivity and compactness

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(by way of average reciprocal distance) are considered with and without the benefits of preparedness (p) and recovery actions (r).

Preliminary experiments involving four carefully designed 10-node complete, hub-based, grid and random networks were completed (Chen and Miller-Hooks, 2012). A concept of resilience in which recovery actions were possible was tested. However, no preparedness options that can improve a network's coping capacity and support recovery actions were considered in the study. Results of these runs indicated that topological structures with limited redundancies faired worst when no recovery actions were supported; however, even with limited or modest budgets to support recovery options, improvements in resilience levels were achieved. It was also noted that improvements were greatest for networks with hubs. This is because exercising only a few options could restore connectivity between a large number of O–D pairs. Network structures that traditionally fare poorly when considering only the network's coping capacity (i.e. where no budget is available for response actions), performed well by focusing recovery actions on the most critical links. These experiments involved very small networks of only four topological classifications applying only one concept of resilience. A more comprehensive analysis from which significantly deeper and broader insights can be garnered is presented herein.

The studied network topologies are introduced in the next section. Measures for their characterization, such as diameter, betweenness centrality and the Shimbel index, are also discussed. This is followed by methods for measuring maximum resilience with respect to the chosen throughput, connectivity and compactness metrics. The experimental design, numerical results and analysis follow. Finally, conclusions and implications of the findings for transportation applications are discussed.

Table 1
Typical graph-theoretic network measures.

Index	Expression	Range	Note
Connectivity			
Cyclomatic number	$\mu = e - v + G$	$0 \leqslant \mu$	Number of fundamental circuits in the network
Alpha index	$\alpha = \frac{\mu}{2v-5}$	$0 \leqslant \alpha \leqslant 1$	Ratio of number of cycles to possible maximum number of cycles
Beta index	$\beta = \frac{e}{v}$	$0 \leqslant \beta$	Ratio between number of links and number of nodes, equivalent to average degree
Gamma index	$\gamma = \frac{e}{3(v-2)}$	$0 \leqslant \gamma \leqslant 1$	Ratio of number of links to maximum possible number of links
Average degree	$\bar{d} = \frac{\sum_i n_i}{v}$	$\bar{d} \geqslant 0$	Average number of arcs incident on the nodes
Cyclicity	$\hat{c} = \frac{\sum_{j=1}^{n} Cycle_i}{\lvert R \rvert}$	$0 \leqslant \hat{c} \leqslant 1$	Number of times random walk led to a cycle back to a previously visited node/number of random walks

Index	Expression	Note
Accessibility		
Diameter	$D = \max(d_{ij})$	The maximum distance among all shortest distances between all O–D pairs in the network
Average Shimbel index	$A_i = \frac{\sum_{j=1}^{n} d_{ij}}{v-1}$	Average of the sum of the lengths of all shortest paths connecting all pairs of nodes in the network
Betweenness centrality	$BC_i = \frac{\sigma_{jk(i)}}{\sigma_{jk}}$	Number of times a node is crossed by shortest paths in the graph

Note: e – number of links in the graph, v – number of nodes in the graph, G – number of sub-graphs in the graph, n_i – number of arcs incident on node i, d_{ij} – distance of shortest path between O–D pair (i,j), $Cycle_i$ – number of times random walk cycled back to node i, $|R|$ – number of random walks, σ_{jk} – total number of shortest paths from node j to k, $\sigma_{jk(i)}$ – number of shortest paths from node j to that pass through node i.

2. Literature review

Many works have proposed measures to characterize networks and their performance for a range of applications, including physics, geography, the Internet, and biological and social systems. Early examples include Kansky (1963), Hagget and Chorley (1967) and Garrison and Marble (1974). Kansky (1963) considered nodal importance and network complexity in transportation networks with three main indices: Alpha, Beta, and Gamma indices, all measures of connectivity. These and other measures are defined in Table 1 of the next section. Their studies, however, were hampered by limited computational resources.

More recently, a number of works have investigated relationships between network shape and transportation system layout, including, for example, road and air networks (e.g., Gastner and Newman, 2006; Reggiani et al., 2011) and subway networks (e.g., Derrible and Kennedy, 2010). Random, scale-free and small-world network structures were found to be particularly relevant as demonstrated through the following example works of this type. In random graphs, nodes are randomly linked with an equal probability of placing a link between any pair of nodes. As defined in Barabási and Albert (1999), a scale-free network has a nodal degree distribution that follows a power law. Thus, some nodes have a degree that greatly exceeds the average. Small-world networks, on the other hand, are densely connected in local regions, creating highly connected subgraphs with few crucial connections between distant neighbors. Wu et al. (2004) showed that scale-free type characteristics exist in urban transit networks in Beijing, while Latora and Marchiori (2002) suggested that the Boston subway system has a small-world network structure. Watts and Strogatz (1998) studied the performance of neural and power grid networks in terms of shortest average path length and clustering. They found that some neural and power grid networks have the shape of small-world networks. Zhao and Gao (2007) studied the performance of small-world, scale-free and random networks in terms of total travel time and traffic volume in the context of a traffic network.

Other works have studied connections between system topology and performance. In the context of transit networks, Li and Kim (2014), for example, proposed a connectivity-based survivability measure to study the Beijing subway system. Similarly, Rodríguez-Núñez and García-Palomares (2014) presented a vulnerability measure and applied it to study the Madrid Metro. In work by Derrible and Kennedy (2010), the robustness of 33 metro systems around the world was investigated. In their work, robustness is defined in terms of cyclicity. Cyclicity is a connectivity measure that like average degree is used to characterize a network topology herein. Exploiting noted relationships between these real system layouts and scale-free and small-world network structures, they provided strategies for improving performance of both small and large systems. They provide a comprehensive review of related works, as well. O'Kelly (forthcoming) discusses the role of hubs in network vulnerability and resilience of various network structures. Finally, Reggiani et al. (forthcoming) propose the use of connectivity as a unifying framework for considering resilience and vulnerability in relation to transport networks. They test this concept through a synthesis of related literature. Numerous additional articles consider the performance of specific transportation networks under various resilience-related measures, but they do not investigate the general role of network topology.

Different from earlier works that studied relationships between network topology and vulnerability or similar measures, this paper investigates the role of network topology in system resilience using a definition of resilience that accounts not only for the network's inherent coping capacity, but also its ability to efficiently adapt post-event.