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Structural robustness of city road networks based on community

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ABSTRACT

Road network robustness is the ability of a road network to operate correctly under a wide range of attacks. A structural robustness analysis can describe the survivability of a city road network that is under attack and can help improve functions such as urban planning and emergency response. In this paper, a novel approach is presented to quantitatively evaluate road network robustness based on the community structure derived from a city road network, in which communities refer to those densely connected subsets of nodes that are sparsely linked to the remaining network. First, a road network is reconstructed into a set of connected communities. Then, successive simulated attacks are conducted on the reconstructed road networks to test the performance of the networks under attack. The performance of the networks is represented by efficiency and the occurrence of fragmentation. Three attack strategies, including a random attack and two intentional attacks, are performed to evaluate the survivability of the road network under different situations. Contrary to the traditional road segment-based approach, the community-based robustness analysis on a city road network shows distinct structural diversity between communities, providing greater insight into network vulnerability under intentional attacks. Six typical city road networks on three different continents are used to demonstrate the proposed approach. The evaluation results reveal an important feature of the structure of city road networks from a community-based perspective, i.e., that the structure is robust under random failure but fragile under intentional attack. This result is highly consistent in different city road network forms.

1. Introduction

The road network is the fundamental infrastructure of a city because it is the main carrier of socio-economic activities as well as cargo transportation. From the network topology perspective, the operational efficiency of a road network is highly dependent on the network structure (Xie & Levinson, 2007). Therefore, understanding the structural robustness of a road network is a major concern for city planners and traffic management at all levels (Kaysi, Moghrabi, & Mahmassani, 2003; Scott, Novak, Aultman-Hall, & Guo, 2006). Originating from studies of complex networks, the concept of robustness, or vulnerability to attack, denotes the decrease of network performance due to the selected removal of nodes or edges (Holme, Kim, Yoon, & Han, 2002). A robustness analysis of road networks can help identify the most important streets or locations that have the potential to more significantly influence the efficiency of the whole road network (Yin, Madanat, & Lu, 2009). Furthermore, a better understanding of road network structural robustness can help improve the robustness of existing road networks in road planning and traffic guidance (Santos, Antunes, & Miller, 2010; Zhang & Levinson, 2008).

Most previous studies on robustness analysis of road networks have focused either on identifying vulnerable links/sections of road networks (Demsar, Spatenkova, & Virrantaus, 2008; Jenelius, Petersen, & Mattsson, 2006) or on examining the accessibility of the whole network/certain zones after natural disasters (Berdica, Eliasson, Nicholson, & Dantas, 2004; D'Este & Taylor, 2003). However, those studies tend to evaluate the vulnerability of certain road segments independently, without considering the relationship between road segments. Although traffic incidents occur on specific road segments or at junctions, they will usually result in traffic changes on neighboring road segments. This fact suggests that the examination of road network robustness should be conducted with a more comprehensive model that considers the influence of attacks on neighboring road segments.

Recently, researchers have found that a group of highly related nodes in a network can provide more structural information than a single node. For example, a stroke in a city road network is a group of adjacent road segments that can reflect the linear nature of streets (Jiang, Zhao, & Yin, 2008). This idea originated from space syntax, where strokes that are used to represent the relatively simple linear elements readily perceived in a network can reflect the lines of flow or movement within the network itself and so constitute natural functional units (Thomson, 2006). Based on this definition, the strokes in a city road network usually represent one

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or more streets. In real road networks, a traffic incident may, under normal circumstances, affect several spatially adjacent road segments and junctions that are located on different streets and rarely perturb the traffic flow of the entire street. Thus, a stroke is usually too long to represent the traffic interaction units of road segments. Because it does not consider the 2-dimensional topological connection between road segments, the stroke-based approach is unsuitable for road network robustness analysis. In network science, community detection offers a novel way to group highly related nodes based on the 2-dimensional topological connections between nodes in a network. Communities, also called clusters or modules, are groups of nodes that are densely connected to each other and sparsely linked to the remaining network (Fortunato, 2010; Gulbahce & Lehmann, 2008). With community detection, nodes with many connections can be identified within the original networks. One can then study the reconstructed network, where nodes are derived from communities and connections between communities are represented as edges. In this way, one attains a coarse-grained description of the original network from a modular view (Fortunato, 2010). Communities in social networks, such as families, friendship circles, and scientific collaboration, have been widely studied for a long time (Moody & White, 2003). Recently, community structure has been shown to widely exist in many network systems, including biological, computer science, and economic networks. For example, in protein–protein interaction networks, communities may correspond to groups of proteins having the same specification within a cell (Chen & Yuan, 2006). In Internet networks, communities exist in groups of pages dealing with the same or related topics (Dourisboure, Geraci, & Pellegrini, 2007). In online markets, such as eBay's bidding data networks, communities can reflect bidders' broad categories of interests (Jin, Parkes, & Wolfe, 2007; Reichardt & Bornholdt, 2007).

However, attention has not yet been paid to communities in city road networks. Intuitively, city road networks also contain modules such as traffic zones or business districts. The road segments in these areas are densely connected with each other. Communities provide a novel way to gather topologically densely connected road segments. In this paper, we identify the communities in city road networks to gain insight into the structural properties of community-based networks.

Moreover, we provide a practical procedure to analyze the structural robustness of city road networks from the community perspective. A quantitative analysis approach is implemented to evaluate the robustness of city road networks under attacks using community-based networks.

The paper is organized as follows: In the second section, six real-world city road networks are introduced as experimental data, and the basic idea of adopting the community perspective into the city road network is briefly described. Then, the community-based city road networks are generated from the experimental data and their characteristics are discussed from the community perspective. In the third section, we outline a practical procedure for evaluating the structural robustness of city road networks as well as our experimental process and main results. The process of the experiments and flow design, including parameter selection, are discussed in detail. Discussions including simplification, limitations, and the implications for further work are provided in the fourth section. We summarize our conclusions in the final section.

2. Experimental data and community detection

2.1. Experimental data

Different cities have different road network forms. These differences are caused by physical conditions, historical development, urban planning, and land use policies. To avoid biased conclusions, six city road networks were selected in this research as the experimental data: two European cities, London and Paris; two North American cities, San Francisco and Toronto; and two Asian cities, Singapore and Beijing. The first five road networks were downloaded from the Open Street Map databases (http://www.openstreetmap.org/), and the last road network was obtained locally.

2.2. Community detection in city road networks

The road segment is the basic unit in current city road network analysis. Traditional GIS (Geographic Information System)-based network analysis organizes road segments as primal graphs, where a node represents a junction, while a road segment between two junctions is treated as an edge (Curtin, 2007). This representation is easy to understand and implement and it provides a straightforward mechanism to capture spatial data through digitizing (Curtin, 2008). However, the topological relationship between road segments is difficult to describe in this primal graph structure. To address this problem, space syntax experts have provided a new representation to make roads the objects of interest rather than junctions. This network representation is called a segment-based dual planar graph, where road segments are represented by nodes and the direct connections between road segments through junctions are mapped to the edges (Batty, 2004; Hillier, 1996; Jiang & Claramunt, 2004; Porta, Crucitti, & Latora, 2006).

Unfortunately, neither segment-based primal graphs nor segment-based dual graphs can give a clear overview of how closely the road segments are connected. The closeness of connections between road segments is very important for robustness analysis because the traffic flows on closely connected road segments can easily influence each other. If the road segments are treated separately, the interactions between road segments are inappropriately ignored.

To overcome this limitation, we introduce the concept of community in complex network theory to represent a group of densely connected road segments. In complex network theory, a community is defined as a sub-graph such that each node has more connections within the community than with the rest of the graph (Radicchi, Castellano, Cecconi, Loreto, & Parisi, 2004). The concept of community can be introduced into city road network studies to represent a group of highly clustered road segments that are densely connected to each other. These densely connected road segments are treated as one unit, which represents the node in a community-based road network in this article. Fig. 1 shows the general idea of extracting communities from a part of a city road network. Fig. 1a shows the initial city road network, where the edges are road segments and nodes are junctions. Fig. 1b is the corresponding segment-based dual graph, where the road segments are mapped into nodes while the edges represent the connections between road segments. Then, community detection is carried out by clustering nodes in the dual graph where nodes are close to each other. The closeness between nodes is measured by distance or other similarity metrics depending on the specific detection algorithms. There are two major categories of community detection algorithms with opposite processes: agglomerative algorithms and divisive algorithms. In agglomerative algorithms, the nodes are iteratively merged into one community if their closeness is sufficiently high, while in divisive algorithms, edges connecting nodes with low closeness are iteratively removed, causing the graph to split into communities (Fortunato, 2010). Fig. 1c presents a diagrammatic sketch for generating a community-based graph from a segment-based graph. The nodes represent the communities, and the edges are the connections between them.

In this article, we detect communities from the segment-based dual graph using the label propagation-based detection algorithm