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Robustness of city road networks at different granularities

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HIGHLIGHTS

- Robustness of a city road network is sensitive to the representation granularity.
- The geographical form is irrelevant to the robustness of a city road network.
- The topological structure is essential to the robustness of a city road network.
- The critical point of network splitting is a failure threshold for urban traffic.

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ABSTRACT

The city road system, as well as other complex systems, can be modeled as networks. Studies investigating the relationship between network structure and functionality provide a novel perspective to investigate the robustness of a city road network by analyzing its structure. The fact that different events may lead to different levels of traffic interruption requires that the investigation on the robustness of city road networks be conducted at multiple granularities. In this study, road networks are modeled at three different granularities: segment-based, stroke-based and community-based model to investigate the response of road networks under punctiform, linear and zonal traffic interruptions respectively. An empirical study with six city road networks around the world shows that the topological structure, especially the diversity level in the betweenness centrality distribution of the network, is more essential to the robustness of the city road network than geographical features and inherent attributes. The performances of city road networks under attacks are consistent in different cities due to the similarity in their topological structures but differ by granularity because city road networks modeled at different granularities have different topological structures. This variation illustrates that the robustness analysis of city road networks should be modeled at the appropriate granularity for a given traffic situation. Furthermore, empirical results suggest that the tolerance threshold for urban traffic is the critical point where the city road network begins to split into several components. The robustness analysis solution proposed in this article can identify these critical points to provide an early warning in urban traffic interruptions.

1. Introduction

The robustness of a city road system refers to its ability to maintain the functionality under attacks or failures. Similar to other complex systems, a city road system can be modeled as a network, where road entities are nodes and the connections

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between these road entities are edges. Investigating the robustness of road networks can help identify the streets or locations that most strongly affect the efficiency of the entire road network and thereby require more attention or planned protection strategies [1]. Robustness analysis can also describe the performance of a city road network under pressure and provide an early warning of traffic events. Furthermore, a better understanding of structural robustness can help improve existing road networks by considering network robustness in road planning and traffic guidance [2,3]. Thus, the study of the structural robustness of city road networks is an important research area for urban planners and transportation managers at all levels.

The structural robustness of networks subject to various attacks is an important research area in complex network studies. Many studies have analyzed how imposed restrictions or attacks affect the topological characteristics and performances of networks. By observing the performance of a network after a series removal of nodes, the previous research found that inhomogeneously wired networks, especially scale-free networks, are robust under random failures of nodes but extremely vulnerable to attacks that target important nodes [4]. These studies on the relationship between network structure and functionality in complex networks suggest that topological structural diversity is essential to network robustness. With a higher level of degree diversity, the network displays a higher level of tolerance to random failures but is more vulnerable to attacks targeting high-degree nodes [4,5].

This phenomenon has been proven to exist in many realistic networks, including artificial networks, such as the North American power grid [6] and water distribution networks [7] as well as public transportation networks. Angeloudis and Fisk [8] collected a database from the world's largest subway systems and found that these subway networks have high connectivity and low degree. Such networks show robustness to targeted attacks that are at least as good as those of scale-free systems. Derrible and Kennedy [9] argued that the robustness of a network depends on the total number of paths available or alternative routes. Therefore, they used the number of cycles present in the system (i.e., the number of loops) as an indicator to evaluate the robustness of networks. Their empirical results from 33 metro systems around the world suggested that more clustered networks generally perform better in terms of robustness because they have generated a significant amount of alternative routes. Zhang et al. analyzed the robustness of the subway network in Shanghai, China and found that it is robust against random attacks but fragile to targeted attacks [10].

Such conclusions, however, cannot be drawn directly to the robustness of city road networks because the road networks are generally much larger and more complex than these networks mentioned above. Since previous studies have proven that the efficiency and robustness of a city road network strongly depend on its structure [11], describing the structural complexity of a road network is a fundamental issue. Porta et al. [12,13], Crucitti et al. [14], Lämmer et al. [15] and Jiang [16] compared structural characteristics using metrics from complex network theory in many cities around the world without providing quantitative conclusions on the structural robustness of city road networks.

Jenelius et al. [17] provided a practical framework to evaluate the robustness of a simplified national road network in north Sweden. The robustness was evaluated by observing structural changes in the network after the removal of randomly selected roads or intentionally selected important roads. This framework primarily focuses on the importance of certain roads. The robustness of the entire network and a comparison of different networks, however, were not addressed. A series of studies inspected the topology and robustness of the city road system under successive attacks [18], following the approach of Albert et al. [4]. In these studies, a definite road (a series of road segments with the same name) is represented as a node and the connection between two definite roads is represented as an edge in a road network. Different successive attacks, including random and targeted attacks, are carried out to evaluate the robustness of the road system in a particular city.

These works illustrate that similar to other complex networks, the robustness of a city road network highly depends on its structure. However, these previous analyses are insufficient in the following aspects. First, different from other artificial networks, the formation of most city road networks experienced a very long period of time. The evolution of city road networks can be influenced by the global planning strategy as well as the local optimization mechanism [19]. Therefore, due to physical conditions, historical development, urban planning, and land use policies, different city road networks have different geographical features. For example, most European cities are described as irregular and self-involved, while most American cities are seen as grid-like networks [20]. Whether the variety of geographical forms will cause different levels of robustness between different cities remains unknown. Second, the usage of each road is different as the traffic system evolved. Some roads are more frequently used than other roads. Whether or not should the city road network robustness analysis take this inherent attribute of road into consideration was not discussed in previous studies. Third, many events may lead to a disturbance of city road networks, and different types of events may lead to different levels of damage to networks. For example, small traffic accidents only affect certain road segments, causing punctiform traffic interruptions. Infrastructure maintenance or traffic control for events like marathons usually acts on a series of linear connected road segments, leading to linear traffic interruptions. Serious traffic accidents or the movement of a crowd before or after large events may result in a zonal traffic paralysis. Therefore, the network topological structure, the most generally acknowledged factor that affects the robustness of a network, should be characterized at different granularities according to the different levels of damages. Fourth, it is known that networks have certain capabilities to tolerate errors [4]. Networks can maintain their functionality when suffering a small amount of failures. Most previous works only focused on the impact of single road entity failure. They did not provide a tolerance threshold when the whole network will malfunction from a holistic view.

Based on these insufficiencies, we generated a series of experiments to reveal whether and how the geographic features and road inherent attributes affect the evaluation of road network robustness and how the topological structure can be used. In this article, we used three granularities to model city road networks: the road segment granularity to evaluate the damage of punctiform traffic interruptions, the stroke (a series of linear connected road segments) granularity to evaluate