Robustness based resilient transportation system study – a case of Urumqi Municipality

Yichang Jiang[1a], Junwei Xuan[2b], Wei Zhao[3c], Xiaohui Ding[4d*], Weizhou Zhong[4e]

1Yantai automobile engineering professional college, Yantai 265507, China

2 College of Grassland and Environmental Science, Xinjiang Agriculture University, Urumqi 830052, China

3 Department of Automobile Engineering, Shaanxi College of Communication Technology, Xi'an 710021, China

4 School of Economics and Finance, Xi'an Jiaotong University, Xi'an 710061, P.R.China

[a] ytqcxy@163.com, [b] sd1900@163.com, [c] zhaowei811124@tom.com, [d] xhding@mail.xjtu.edu.cn, [e] weizhou@mail.xjtu.edu.cn

Key words: road network; robustness analysis; simulated successive attack; Urumqi Municipality

Abstract: Maintaining the resilience of transportation system is crucial for the overall sustainability of a city. As a complexed system, the city road system can be modeled as networks. Studies investigating the relationship network structures and functionality provide a novel perspective to investigate the robustness of a city road network. In this study, the road network of Urumqi Municipality was modeled at three different spatial scales: road section, road name and road community, to investigate the response of road network under two attack strategies – random and initial degree based attack. The performance of road network are diversified at three spatial scales under different strategies, which help to pinpoint two major weakness of network robustness: relatively low efficiency of network connectivity at road section scale, and key roads that vulnerable to intentional degree based attack strategy at road name scale. Whereby, suggestions are propounded against this two weaknesses for solidify the resilience of the road network of Urumqi Municipality.

Introduction

Cities and traffic have developed hand-in-hand since the earliest large human settlements. As windows into the complex world of urban systems, we can therefore better understand its encompassing urban system by properly characterizing a road network. There is growing interests of emerging studies in recent years on the robustness of road networks, including network design, travel behavior under conditions of uncertainty and the definition of reliability measures for networks [1, 2]. However, along with the expanding of urban system and increasing complexity, the road system itself in urban area shows signs of a living self-organizing system [3], the characteristics of which can hardly be delineated solely by robustness.

The concept of resilience has been used in ecology and interdisciplinary science for nearly 40 years [4, 5]. Contemporary definitions consider resilience to consist of (1) the amount of disturbance that a system can absorb while still remaining within the same state or domain of attraction; (2) the degree to which the system is capable of self-organization (versus lack of organization or organization forced by external factors); and (3) the degree to which the system can build and increase its capacity for learning and adaptation [6]. Furthermore, as with resilience, it must be defined in relation to a given perspective and problem. Therefore, in the context complexed urban system, the resilience of road system can be defined as the capability of the transport system to repeatedly recover, preferably within a short time period, from a temporary perturbation.

As the key influences that impact on the target (desired or tolerable) level of resilience of road system are multiplied, including life safety, disruption, loss of access for emergency services, need for lifeline restoration, wider economic impacts, etc. [7]. The main focus of this study is to extend the idea of resilience into the conventional study of the robustness of road network system, and a case study was performed in Urumqi Municipality, Xinjiang Uygur Autonomous Region.

Method

Research area

As the political, economic, cultural, and technological center, Urumqi Municipality is located at the north part of Xinjiang Uygur Autonomous Region (abbreviated as Xinjiang). As the capital of Xinjiang, the geographical advantage of Urumqi Municipality – centered in the Asian Continent, endows this city as the central hub of the transportation and logistics, connecting Xinjiang and hinterland of China.

Road system of this city is composed by the express road system (ERS) (Fig. 1), including Urban Express Ring Road, Hetan Road, Xihong Road, Kashi Road, Xishan Road, etc; Trunk road system (TRS), including Altay Road, Guanchangchun Road, Liyushan Road, Youhao Road, Yangtz Road, Beijing Road, Nanhu Road, Hongshan Road, Qingnian Road, Xihong Road, Qidaowan Road, etc; Secondary roads system (SRS) and branch systems (BS). According to the planning of Urumqi, the length of the TRS is 274 km, with a road density of 1.37 km/km2, and the length of the SRS is 326 km, as with a road density of 1.63 km/km2.

Influenced by mountainous territory in the Northern and Southern parts of the city, historical and other factors, there is still large room for optimization of the road network system and grade configuration of Urumqi Municipality.

Topological properties of the road network

In order to identify the characteristic of the urban road network, the actual urban road network need to be abstracted to a topology graph first, composed by nodes and edges. In this research, through comprehensively adopting the road map of Urumqi Municipality, data from Baidu Map and Google Map, as raw data, and the ArcGIS Platform, we extracted the topology graph of the road network of Urumqi Municipality, composed by 132 roads (including TRS, SRS and BS) (Fig. 1).

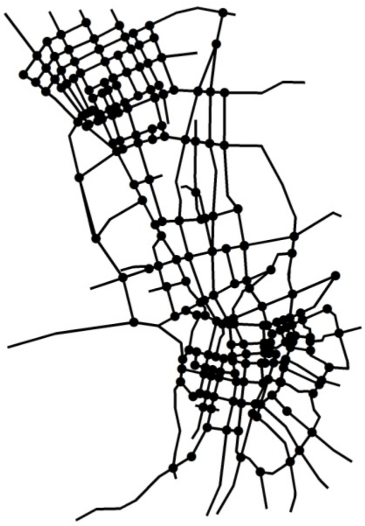

Fig. 1 Topology of the road system of Urumqi Municipality

Thereafter, the multi-level road network model is building at three spatial scales, namely road section, road name and road communities, based on the topology of the road system of Urumqi Municipality. The road network model at road section scale is taken for uncovering the proximity relation between road sections, by which the road sections was mapped as nodes and the road crossings as the edges in the topology graph. Road name is the instruction system of a road, and, to a certain extent, indicates the characteristics of flows of goods and people. The roads with same road name are taken as the nodes, and crossings between roads with different names as edges. Community, as an important notion of complex network at meso-level, is suitable for representing the local area network composed by roads among neighborhoods and communities. Thus, the road network model at community scale enables the analysis of the robustness of road system from a more macro perspective.

The multi-level road network models in this study were built by the Dual Approach method. Additionally, the community network topology of the road network of the research area was derived by adopting the multi-Level Louvain method [8]. Based thereon, major topological properties – the degree distribution, the clustering coefficient, the average path length, and the global and local efficiency, were analyzed.

- Degree distribution

The degree of a node is the number of edges incident with the node. The degree k_i of node i is defined as $k_i = \sum_{j\in G} a_{ij}$. The degree distribution is $\langle k\rangle = 1/N \sum_{j\in G} a_{ij} = 2K/N$.

- Clustering coefficient

Clustering is a property found in many real-world networks. For instance, in social systems there is a high probability that two individuals linked by an acquaintance have a third acquaintance in common. Such tendency can be measured by the clustering coefficient C. For each node i of G, we consider the subgraph G_i of its first neighbors, that is obtained in two steps: (1) extracting i and its first neighbours from G; (2) removing the node i and all the incident edges. If node i has k_i neighbours, then G_i will have k_i nodes and at most $k_i(k_i-1)/2$ edges. C_i is proportional to the fraction of these edges that really exist, and measures the local group cohesiveness of vertex i. C is the average of C_i calculated over all nodes:

$$C(G) = \langle C_i\rangle = \frac{1}{N}\sum_{i\in G} C_i \tag{1}$$

Where

$$C_i = \frac{2e_i}{k_i(k_i-1)} = \frac{\sum_{j,m} a_{ij}a_{jm}a_{mi}}{k_i(k_i-1)} \tag{2}$$

where e_i is the number of edges in G_i. By definition C, takes values in the interval [0,1].

- Average path length

The average path length, denoted by d, is the average distance between all pairs of nodes in the network. For a directed network of d nodes, d is

$$d = \frac{1}{N(N-1)}\sum_{\substack{i,j=1,N\\ i\neq j}} d_{i,j} \tag{3}$$

Where $d_{i,j}$ is the length of the shortest path between nodes i and j, i.e., the minimum number of edges covered in order to go from i to j.

Robustness and resilience analysis of road network model

A series of experiments were designed to simulate the reaction of city road networks under attacks. Such processes for robustness analysis of the road network were narrated in sequence of index, strategies and evaluation algorithm.

Robustness analysis index

(1) Relative size of the largest connected component

Usually network robustness analysis is concentrating on the critical fraction of attacks at which the network completely collapses. In city road systems, however, the networks may suffer severe damage without completely collapsing. We thus introduced the relative size of the largest connected component S to investigate the impact of attacks on the network structure:

$$S = N'/N \tag{4}$$

where N' is the number of nodes of the largest connected component, N denotes the number of nodes of the whole road network. Before the attack, the S equals to 1. After the attack, the S may turn to descend. Whereby, the relative size of the largest connected component can briefly reflect the damage degree.

(2) Efficiency of network connectivity

Two types of performance, i.e., efficiency behavior and fragmental fraction, are used to evaluate the robustness of city road networks under attack. We evaluate the efficiency behavior from both global and local viewpoints.

The global efficiency E_{glob} is a measure of how well the nodes communicate over the network [9, 10]. The efficiency ε_{ij} in the communication between node i and j is assumed to be inversely proportional to the shortest path length, i.e. $\varepsilon_{ij} = 1/d_{ij}$. In the case G is non-connected and there is no path linking i and j, it is assumed $d_{ij} = +\infty$ and, consistently, $\varepsilon_{ij} = 0$. The global efficiency of a graph G is defined as the average of ε_{ij} over all the couples of nodes [9, 10]:

$$E_{glob} = \frac{1}{N(N-1)}\sum_{i,j\in G, i\neq j}\varepsilon_{ij} = \frac{1}{N(N-1)}\sum_{i,j\in G, i\neq j}\frac{1}{d_{ij}} \tag{5}$$

By definition E_{glob} takes values in the interval [0,1], is equal to 1 for the complete graph, and is correlated to $1/L$ (a high characteristic path length corresponds to a low efficiency). Consistently with the global analysis, we can measure the clustering properties of a graph by using the same measure, the efficiency, at the local level. The local efficiency is defined as [9, 10] (Latora & Marchiori 2001, 2003):

$$E_{loc}(G) = \frac{1}{N}\sum_{i\in G} E(G_i); \quad E(G_i) = \frac{1}{k_i(k_i-1)}\sum_{l,m\in G, l\neq m}\frac{1}{d'_{lm}} \tag{6}$$

where d'_{lm} is the shortest path length between node l and m, calculated in the subgraph G_i. A complex system can be therefore analyzed both at global and local scale by means of a single variable, the efficiency. As for E_{glob}, also E_{loc} is already normalized for topological graphs.

The relative efficiency of communication RE refers to the ratio of efficiency of communication after and before attack, whereby it can be taken to represent the variation of the global network connectivity under different attacking strategies.

$$RE = E_{loc}/E_{glob} \tag{7}$$

Robustness analysis strategies

Non-recurrent failures caused by natural disasters, such as floods and hurricanes, or traffic accidents are more likely to occur randomly on roads. Other incidents, such as terrorist attacks or large events, may occur specifically on important roads. Thus, we chose two types of strategies to test our networks: random and targeted attacks. The random attack strategy is easy to perform by randomly choosing the attacked nodes. In contrast, the targeted attack strategy requires identifying the important nodes. The first one is random attack strategy. This strategy randomly chooses one node at each step and removes the node and all edges linked to it from the network. The loop is performed until the whole network collapses. The performance of the network under attacks in terms of efficiency and fragmentation is measured at each loop to monitor the reaction of the revised network.

The second strategy is the initial degree based attack strategy. We remove the node with the highest degree at each step, calculate the parameters L, C and S, and then recalculate the degree of each node. The removal procedure is repeated until the network collapses.

Suggestion on the resilience of the road network

As a characteristic that indicates system performance under unusual conditions, recovery speed, and the amount of outside assistance required for the restoration to its original functional state [11], resiliency of road network comes from excess capacity that is obtained by over capacitating routes, providing alternate routes, and optimizing the capacity of an existing system with proper coordination and management [12]. In this study, the results from robustness analysis were taken for extracting policy suggestions on enhancing the resilience of the road network of Urumqi Municipality.

Results

Topological properties of the road network model of Urumqi Municipality

The road network models of Urumqi Municipality at different spatial scales – road section, road name and road community scale, were extracted through the dual approach and presented in Fig 2. The topological properties of the road network were thereafter analyzed and presented in Table 1.

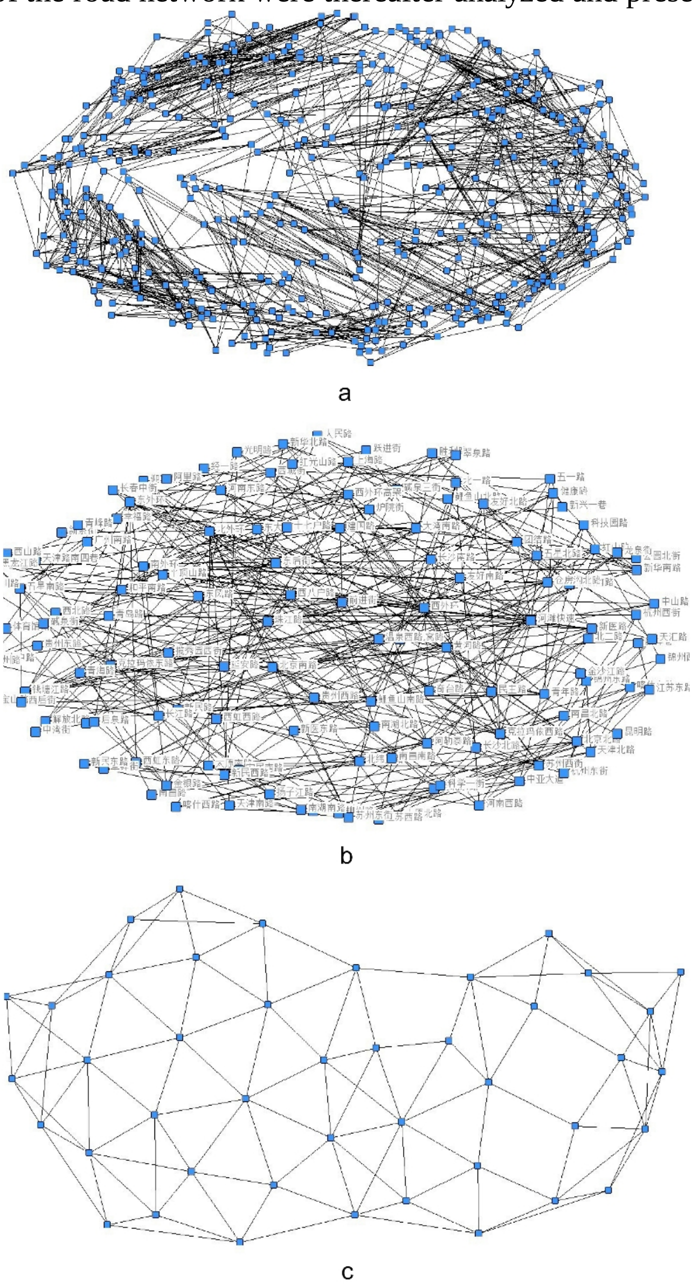

Fig.2 The road networks models of Urumqi Municipality at road section, road name and road community scales

Table 1 Statistical characteristic of road network of Urumqi Municipality

Spatial Scale	Nodes	Degree distribution	Average clustering coefficient	Average path length
Road section	453	5.55	0.49	10.01
Road name	134	5.51	0.22	3.57
Road community	43	5.30	0.46	3.37

The degree distribution of network models at three spatial scales was almost the same. The degree distribution of road section based network was 5.55, with 39.5% of its nodes with degree more than the average level. These roads are key part of the road network and bearing the main tasks of traffic flow, while the rest 60.5% roads are as auxiliary roads for ameliorating the local traffic. As for the road name based and road community based networks, their degree distribution were 5.51 and 5.3 respectively. For the former one, the proportion of nodes with a higher degree than the average level was 40.3%, while this proportion for the later one was 45%. Against the ratio of roads with degree that respectively above and below the average level, the community based road network is more even among the other two, since these road communities are not isolated but rather closely connected.

The clustering coefficient is an indicator used as a local efficiency measurement [13]. The average clustering coefficient of road section based network of Urumqi Municipality was 0.49, which is far larger than that of random network with the same nodes (0.002), which indicates that the correlation among road sections of this network is very tight. The road name based network revealed the same trend as the road section based, but with relative small average clustering coefficient 0.22, against the same coefficient of random network as 0.07 with the same number of nodes. On the contrary, the road community based network, compared with the former two networks, was with a much larger average clustering coefficient as 0.46, against the same coefficient of random network as 0.02 with the same number of nodes. In general, the road network of Urumqi Municipality are much more concentrated than the randomly generated network, and the community based network is with the highest clustering coefficient among the other two networks, which indicates that communities of the road network are more correlated with each other than those randomly chosen road pairs.

The average path length of a network is often taken as a sign of global efficiency of network connectivity. The average path length of road section based road network of Urumqi Municipality was 10.01, which is relatively small compared to the total nodes (453) and edges (1258) of this network. The average path length of road named based network was 3.57, with a total nodes of 134 and edges of 369, and the same index of road community based network was 3.37, with a total nodes of 43 and edges of 114. The road name based and road community based model are with obviously higher global connectivity than road section based network, regardless of the magnitude of these networks. Furthermore, with consideration of the network scale, the road name based network is more efficient from the whole network perspective compared with the road community based network.

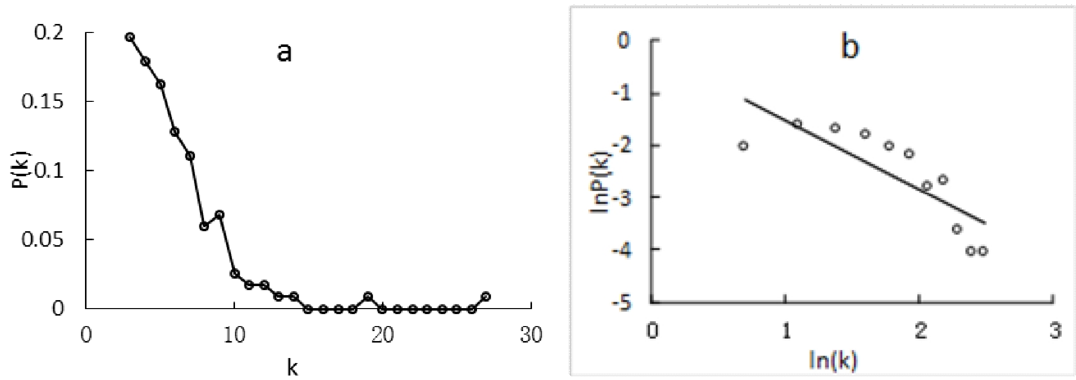

Fig. 2 Degree distribution of road name based network model of road network of Urumqi Municipality (a. planar reference frame, b. log-log coordinate)

Large number of researches on urban road network were performed at the scale of road name, and uncovered that the type of road networks at this scale are dominantly belonged to scale-free network. In this research, the network characteristic of road network of Urumqi Municipality was determined by the log-log plot.

The degree distribution, P(k) of the road name based network of Urumqi (Fig. 2) shows a clear scale-free behavior with an exponent γ=1.43, which indicates that the road network of this city is not homogeneous, and partial roads are encountering more traffic loading, treated as TRS.

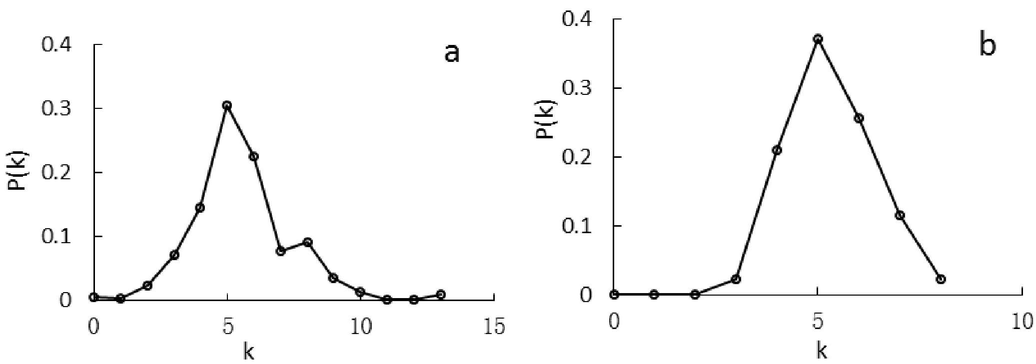

Fig. 3 Degree distribution of road network model (a. Road section scale, b. Road community scale)

The degree distribution of road section based and road community based road networks of Urumqi Municipality was normally distributed, with the most frequently exited degree of 5. Whereby, these two networks of Urumqi Municipality are with no scale-free network characteristics.

Robustness analysis of road network of Urumqi Municipality at three spatial scales

Under the random attack strategy, the maximal connected subgraph of the networks at three spatial scales showed almost the same descend trend as the rate of removed nodes (RRNs) increasing between 0 and 25% (Fig. 4). Then, along with the continuous increasing of RRNs, the road section based network turned to decrease much quicker than the rest two networks, and the whole network collapsed with RRNs reached 80%. While the road named and road community based networks closed to collapse with this rate up to 90%. Such trend may lie on the characteristics of global connectivity of the road section based network, since its average clustering coefficient was 0.49 and its average path length was 10.01, which may lead to the lose of the local connectivity efficiency with partial of its nodes removed. Whereby, the road section based network demonstrated the most severe changes of its network structure under the random attack among the three networks.

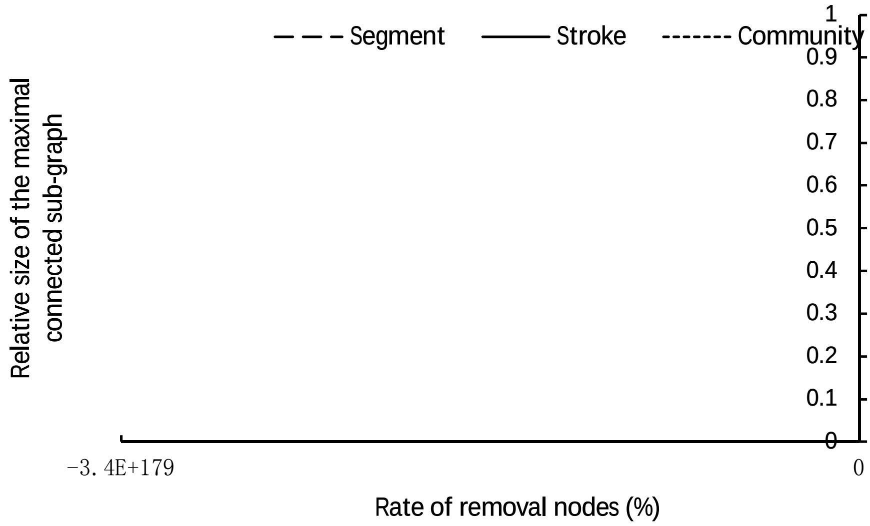

Fig. 4 Comparing of the maximal connected subgraph of road network model of Urumqi Municipality under random attack strategy at three different spatial scales

The maximal connected subgraph can only represent the scale change of network, while the RE can quantitatively denote the network connectivity efficiency before and after the attack. From Fig. 5, the pattern of RE changes are similar under the random attack strategy, but with different decreasing rate. The road section based network lost its network connectivity at much faster rate and the whole network collapsed when RRNs reached 70%. While the rest two networks collapsed when the rate up to 80%. The trend of RE of road network at three spatial scales confirms the results from the former study that the road section based road network is more vulnerable under the random attack strategy, due to the network structure characteristics of high local connectivity and low global connectivity.

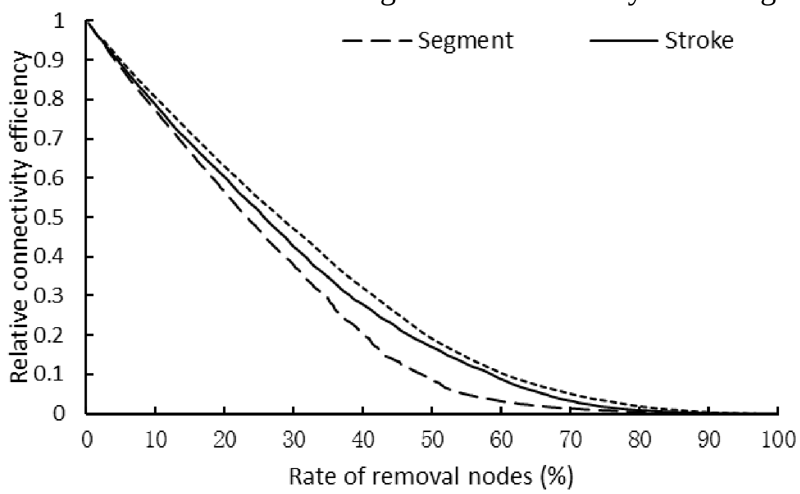

Fig. 5 Comparing of RE of road network model of Urumqi Municipality under random attack strategy at three different spatial scales

From Fig. 6, with RRNs increased from 0 to 20%, the RE of the road network at three spatial scale demonstrated similar decreasing trend under the initial degree based attack strategy. With the further increasing of RRNs, the road name based road network severely lost its RE and collapsed with the rate reached 50%. The road section based and road community based road networks showed much steady descend trend and collapsed when RRNs reached 70% and 80% respectively. Such trend is determined by the topology of these networks, since the road name based road network is scale-free network, and much vulnerable under the initial degree based attack strategy.

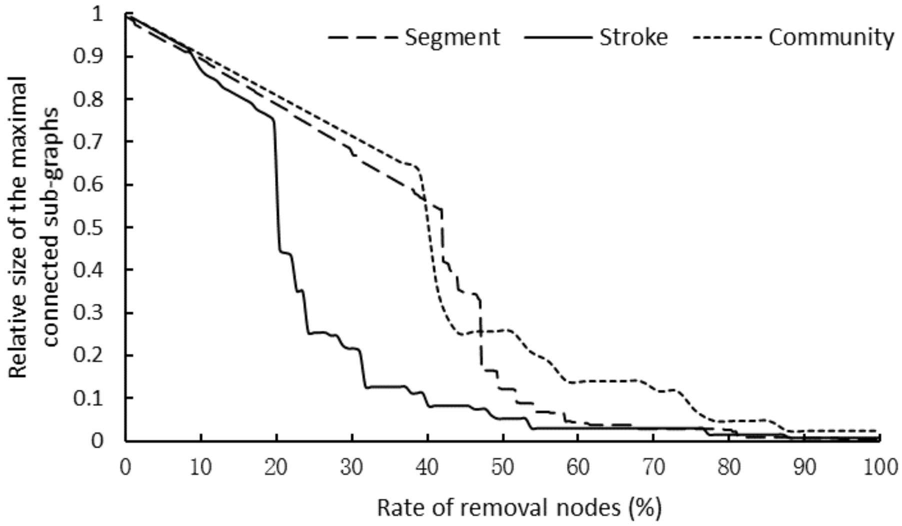

Fig. 6 Comparing of the maximal connected subgraph of road network model of Urumqi

Under the initial degree based attack strategy, the patterns of the three road networks were much alike (Fig. 7). However, the road named based road network deceased at much faster speed compared with the rest two networks, and it collapsed when RRNs reached 70%, while the other two networks collapsed at rate of 80%. In brief, the road section and road community based network showed almost the same trend under the initial degree based attack strategy, while road name based road network showed robustness to random attack but much vulnerable to the degree based attack strategy.

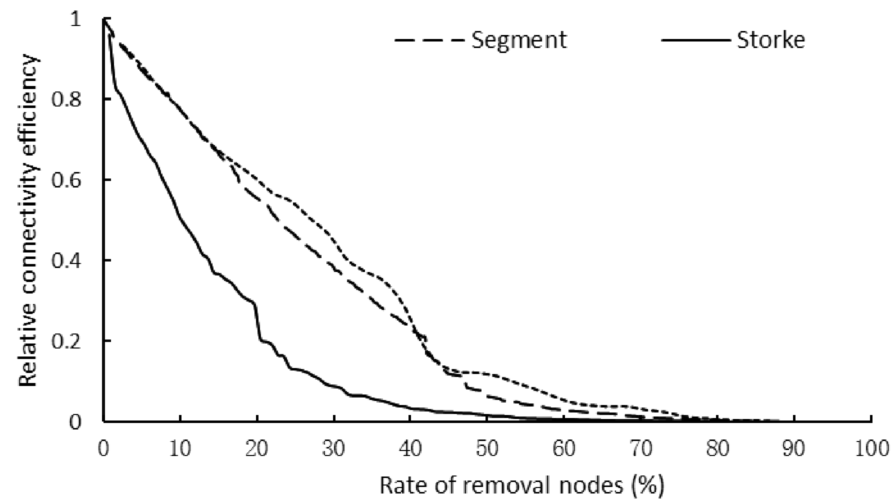

Fig. 7 Comparing of RE of road network model of Urumqi Municipality under the initial degree based attack strategy at three different spatial scales

Suggestions on resilience of road network of Urumqi Municipality

Road network is the most fundamental elements of transportation system, and its resilience is manifested in the redundancy of the road network while facing unexpected accidents (Battelle 2007). In case of road network of Urumqi Municipality, the robustness analysis in this study has pinpointed two aspects with the potential to contribute to the overall resilience of the road network system in this city: relatively low efficiency of network connectivity at road section scale, and key roads that vulnerable to intentional degree based attack strategy at road name scale.

Considering the first aspects, a key countermeasure is to identify the sub-community of road network with low connectivity efficiency and add new branch road to increasing the overall redundancy of the road network. Since the existing road system of this city, with the road grade configuration as 1:0.7:1.3, is far from the planned one as 1:0.7:1.3, there is a large room for such improvement.

As for the second aspects, it roots in the uneven distribution of traffic flow of Urumqi Municipality, which is a common scenario for most cities. Countermeasures should lie on both the node network level as well as road auxiliary facilities. Firstly, new branches should be added to the road network in order to share the traffic load of those major traffic roots, i.e. ERS and TRS of Urumqi Municipality. Secondly, the road auxiliary facilities should be relocated more reasonably, including the scientific arrange the locations of the bus stations, rationally determining the number and distribution of the side road exit, optimizing the traffic indication system and regulation, etc.

Conclusion

In this article, we proposed a comprehensive analysis procedure on assessing the robustness of road networks, and proposed suggestions on improving the resilience of the road networks of Urumqi Municipality. The analysis carried out in this article was based on static road networks without considering dynamic traffic flows. The robustness analysis in this research have pinpointed the two major weakness in the road networks of Urumqi Municipality, and thereby targeted measurements were propounded for enhance the resilience of the road network. The results in this research are with reference value to those cities with similar road network systems and help them to optimize their road networks from the robustness perspective.

Acknowledgements

Financial support came from the National Science Foundation for Post-doctoral Scientists of China under grant No. 2013M542336, the National Natural Science Foundation of China No. 71172184, and the Fundamental Research Funds for the Central Universities No. SK2014044. Their supports are gratefully acknowledged.

References

[1] M. G. H. Bell, Cassir C. Reliability of Transport Networks. Research Studies Press, Baldock, Herthordshire, England, 2000.

[2] M. G. H. Bell, and Iida Y. (Eds) The Network Reliability of Transport, Proceedings of the 1st international symposium on transport network reliability (INSTR), Pergamon, Oxford, 2003.

[3] I. L. H. mmers, P. van Koningsbruggen. Selforganisation in the transport sector, In Proceedings of the ECCON 2001 Annual Meeting on Chaos and Complexity in Organisations, Lage Vuursche, 2001.

[4] C. S. Holling. Resilience and stability of ecological systems. Annu Rev Ecol Syst 4(1973) 1–23.

[5] C. S. Holling. Understanding the complexity of economic,ecological, and social systems. Ecosystems 4 (2001) 390–405.

[6] S. R. Carpenter, M. Walker, J. M. Anderies, N. Abel. From metaphor to measurement: resilience of what to what? Ecosystems 4(2001) 765–781.

[7] P. Brabhaharan. Recent advances in improving the resilience of road networks. NZSEE Conference, 2006.

[8] T. Aynaud, V. D. Blondel, J. L. Guillaume, R. Lambiotte. Optimisation locale multi-niveaux de la modularité (in French) Chapitre 14 in: Partitionnement de graphe Optimisation et applications, Charles-Edmond Bichot et Patrick Siarry (Eds), Hermes, Paris, 2010.

[9] V. Latora, M. Marchiori, Phys. Rev. Lett. 87 (2001) 198701.

[10] V. Latora, M. Marchiori, Eur. Phys. J. B 32 (2003) 249.

[11] P. M. Murray-Tuite. A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions. Simulation Conference, WSC 06. Proceedings of the Winter, 2006.

[12] Battelle. Evaluation of system's available redundancy to compensate for loss of transportation assets resulting from natural disaster or terrorist attacks. Report of the National Surface Transportation Policy and Revenue Study Commission: Transportation for Tomorrow. National Surface Transportation Policy and Revenue Study Commission, 2007.
[13] D. J. Watts, S. H. Strogatz, Collective dynamics of 'small-world' networks, Nature 393 (1998) 440–442.

