Using Graph Model to Analyze the Topological Vulnerability of Transport Infrastructure

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Abstract. Given the ubiquitous nature of infrastructure networks in today's society, there is a global need to understand, quantify, and plan for the resilience of these networks to disruptions. With the development of transport infrastructure, vulnerability analysis is a core process of man-made systems safety management. The main purpose of the paper is to identify the critical road sections and intersections in a road network which have great influence on the normal functionality of the urban territory. In this paper the structure (topology) of highway network of Vladivostok city in Russia was investigated and analyzed based on the graph theory. The network model of the road system was constructed using Open Street Map data.

Keywords: vulnerability, complex networks, topology, transport infrastructure

1 Introduction

The quality of life of people in the present time is largely determined by the state of development of the technosphere. Modern society relies upon the collection of systems and institutions known as the infrastructure to support the welfare and living standard of people. A downside of this dependency is that sudden failures and disruptions in the systems may cause severe strains on the society.

With the development of economies more and more people living in cities, traffic congestion has become a very serious problem in many large cities of the world. Road network disruptions can threaten the possibility for people to receive medical care and other critical services. More generally, they impair people's accessibility to daily activities such as commuting to work and doing the shopping. Furthermore, there may be large costs associated with remedies and restoration of the transport system to a fully operational state.

Due to a number of catastrophic events, vulnerability analysis has been an area of increasing interest and research since the mid 1990's. There have been a number of major events that have disrupted transport networks around the world, but there are also everyday events that can cause disturbances such as accidents, road works or vehicle breakdowns. Disruptions can be caused by a wide range of events, some of

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which originate within the transport system, including traffic accidents and technical failures. Other events are external strains imposed on the system, often caused by nature, as with floods, landslides, heavy snowfall, storms, wildfires, earthquakes, etc. While accidents and technical failures may have limited extents, disruptions caused by nature may cover large areas in the road network.

Vulnerability is a generalized conception. There are a lot of different definitions of vulnerability. Vulnerability is usually portrayed in negative terms as the susceptibility to be harmed. It is degree to which a systemic susceptible to and is unable to cope with adverse effects. The concept of transport infrastructure (road network) vulnerability is not uniform so far [1]. According to the study [2], road network vulnerability is a sensitivity coefficient that is easily affected by accidents and finally makes the service level decline sharply. The service level of a road network describes the probability of the road being connected or used at a certain time. According to Tuyinfei from Tongji University, the networks inability to withstand abnormal events is one of the vital causes of significant losses, and this is one of the properties of a road network that can constitute road network vulnerability [3]. Husdals view is that road network vulnerability describes the non-functioning of a network under certain conditions.

One important observation giving rise to the broader studies of the topology of networks is that “the structure affects function”. In other words, there exists a large extent of interactions between network structure and its dynamics, which makes the study of the network topology crucial. In particular, this is true in the case of technological and physical networks where system topology is formed to support certain activities towards operational and service objectives. Subsequently, any change in the network topology will have consequences in terms of system operation and its ability to function.

According to the former researches, the concept of road network vulnerability is to emphasize the loss or effect after the network has been attacked by an accident [4].

Road network vulnerability analysis can be defined as the study of potential degradations of the road transport system and their impacts on society, modelling the road infrastructure as a network with links (road segments) and nodes (intersections) [2, 5]. Using the Swedish road network as a case study, Jenelius found that the importance of regional road network is largely determined by the road network structure and the average traffic load in the region, whereas the exposure of regional road network is largely determined by the network structure and the average user travel time [6]. The study shows that the long-term vulnerability disparities stem from the fundamental properties of the road system and the population densities. Therefore, different road connections have a great impact on the network vulnerability, and research on the structural vulnerability of road network is very necessary. If we can find the road network vulnerability from the road network structure, then network structure can be optimized to reduce the road network vulnerability.

The main purpose of road network vulnerability assessment is to find the weak element, in other words, to find the key point of the whole network where the loss is the most significant when the same level of attack is suffered. In this paper, we propose the method to evaluate the vulnerability of the network with respect to the loss of a road link, e.g. due to a car accident, road work or other jamming occurrences.

The recent advances in the field of complex networks [7, 8] reveal its promising potential to investigate road networks vulnerability at the systems level from a topological perspective. In graph and complex networks theories, a number of measures have been proposed to characterize networks. Basic characteristics of the transport infrastructure can be applied to assess the vulnerability of the network according to complex network theory. Complex network is an abstraction of real large complicated system, which can depict internal various interaction and relationship in complicated system. This theory has been applied to many real infrastructural networks. Complex network theory with it's random network model, the small-world model and the scale-free network [9–12] is ideal for researching the actual networked systems, such as power grid networks [13, 2], oil/gas pipeline networks [14, 15], urban metro [16], computer and communication systems [17].

2 Topological vulnerability metrics

Graph theory is utilized to study the structure vulnerability of road network. Structural (topological) vulnerability refers to the systems own inherent instability and sensitivity. Road network is taken as undirected graphs which show the general structure of road network without considering the actual flow.

Let us consider a network of roads (hereafter also called links or edges) connecting a number of locations (hereafter also called nodes or vertices). The topology can be represented as a graph $G = (V, E)$, V is the set of nodes, E is the set of edges.

There are several statistical measures commonly used to characterize the structure of complex networks and its vulnerability:

- *degree centrality* $C_D(v) = deg(v)$ is defined as the number of edges connecting with node v.
- *betweenness centrality* $\sigma(v) = \sum\limits_{i \neq v \neq j} \frac{\sigma_{ij}(v)}{\sigma_{ij}}$, where σ_{ij} is the total number of shortest paths from node i to node j and $\sigma_{ij}(v)$ is the number of those paths that pass through v.
- *average path length* $l_G = \frac{1}{n(n-1)} \sum\limits_{i \neq j} d(v_i, v_j)$, where $d(v_i, v_j)$ is the shortest distance between $v_i, v_j \in V$, n is the number of vertices in G.

From the point of view of the topological characterization of the network, centralities are typically used to measure the vulnerability of the nodes. Degree tends to describe the importance of node from the local view, while betweenness tend to describe the importance of node from the overall view.

2.1 Proposed algorithm for edge vulnerability assessment

According to our concept of the topological vulnerability, defined in the introduction together with finding vulnerable nodes we are also interested in failures on the network links. Under the topological edge vulnerability of the road network in this paper will understand the edge weight, defined as the length of the shortest alternative paths through the nodes left after removal checked edge. Thus, the higher is the edge weight, the more vulnerable it is. To access edges vulnerability is proposed an algorithm consisting of several steps.

- Step 1. Finding clusters in the network.
- Step 2. Selecting the links passing through the clusters.
- Step 3. The quantitative assessment of the found edges vulnerability.

OpenStreetMap (OSM) project is proposed to use as a cartographic base [18]. The networkX Python module was implemented to work with network topology. Louvain method and its realisation on a high-level scripting language Python was used for clusters detection [19]. Results of this step are shown in figure 1.

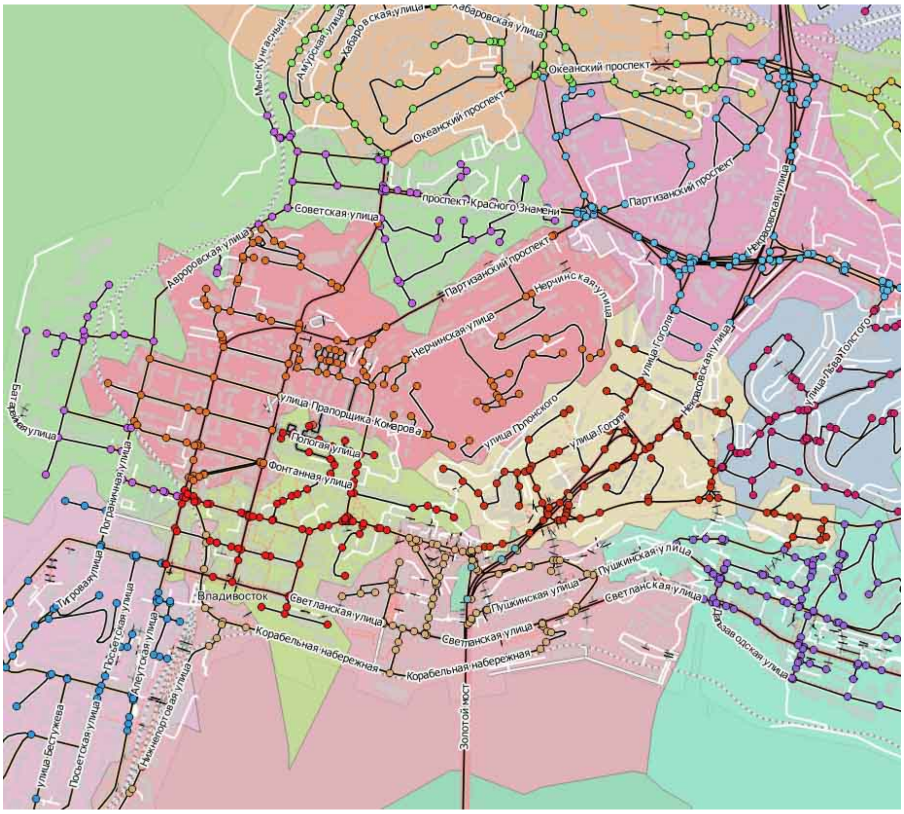

Fig. 1. Borders of the communities

The result of Louvain clustering is a list of vertices with labels as clusters numbers. Therefore, the second step is to traversing the G edge list to find edges which vertices belong to different clusters.

To determine the quantitative value of the topological edge vulnerability used another developed algorithm consisted of five steps.

- Step 1. For all edges set the initial edge weight w equal to $+\infty$.
- Step 2. Remove checked link e_j^c from the network. Save start v_j^s and end v_j^e node.
- Step 3. Find the shortest path through v_j^s and v_j^e nodes and calculate the length l_j^{se} of the route.
- Step 4. If the path exist then $w_j = l_j^{se}$. Restore the e_j^c edge.
- Step 5. Go to next e_{j+1}^c in the list.

The result of the algorithm is the list of edges with their weights. Edges with no alternatives routes have infinity weight. The failures of such links lead to serious consequences. The implementation of this algorithm was also carried out with the python and NetworkX module. The shortest path was calculated with Dijkstra's algorithm.

3 Case Study

3.1 Getting Data from the OpenStreetMap Project

Today OSM map is the only one map that can be downloaded for free on almost any device, and the primary source of geodata for organizations that want to save on a cartography.

More than decade of efforts of numerous volunteers developing the Open Street Map project[18], led to a Grand open database map information for the whole of planet Earth [20]. OSM XML snapshot of the project database is a complete map of the entire planet (a Planet.osm [21]) and in uncompressed form occupies a volume of several hundred gigabytes. Updated every week and grouped by country and region maps in OSM XML formats can be downloaded, for example, via the GeoFabrik website [22]. There are several utilities that can convert osm xml file to shapefile or Postgress/PostGIS [23] database (osm2shp, osmosis, osm2pgsql, osm2pgrouting, osm2po, osm4routing). But some of them are suitable only for rendering purpose and during the convertation lose topological information and some of them difficult to configure. With the prospect of development was developed a program converts the osm xml file in to the SQLite/Spatialite [24] database with TRANSIMS network format [25–27].

3.2 Topological Vulnerability of Vladivostok city highway network

Developed algorithms and programs were applied for construction the network of Vladivostok city in Russia. To obtain Vladivostok city transport network we download OSM XML file with Primorsky region map and prune it with osmosis program and POLY file that describes the city boundaries. The resulting Vladivostok OSM-file contains 132 552 node (node osm) and 7 818 lines (osm way). After the application of the developed program the topology of the Vladivostok city highway network as graph G was built. The network consist of $|V| = 10480$ nodes and $|E| = 12574$ edges.

Figure 2 illustrates a degree distribution of the nodes.

Figure 3 illustrates a scaled to size numerical values of the betweenness centrality nodes measure.

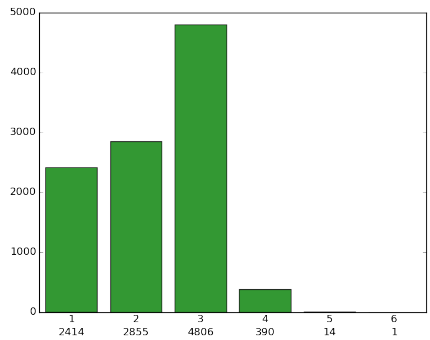

Fig. 2. Degree distribution of the nodes

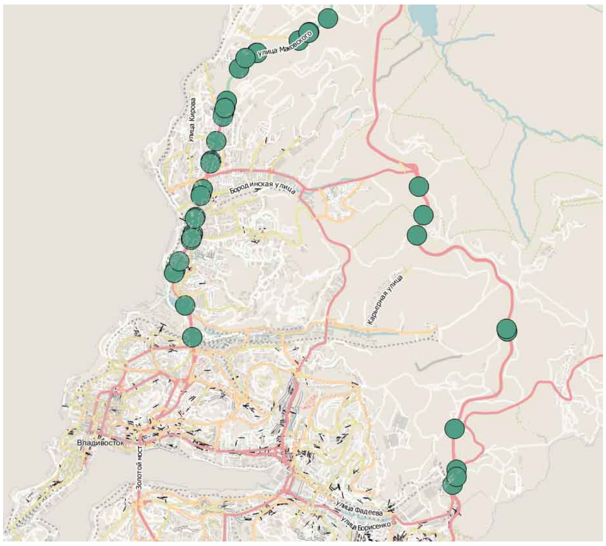

Fig. 3. Scaled betweenness centrality values

Interestingly, such nodes degree distribution is typical for natural structures like cracks on the earth surface or blood vessels. This suggests that the Vladivostok city topology formed in random way.

Betweenness centrality reflects the extent to which a node lies in between pairs or groups of other nodes of the graph. This can be also stated as the extent to which a node is an intermediate in communication over the network. Based on a priori knowing of the special features of the transport streams and problem zones of the Vladivostok city can be said that only a part of the results obtained by the evaluation in line with the real situation. Therefore, the task of developing new assessment remains valid and important.

Figure 4 shows the result of the proposed algorithm implementation. The color gradient from yellow to red indicates the metric value of topological vulnerability.

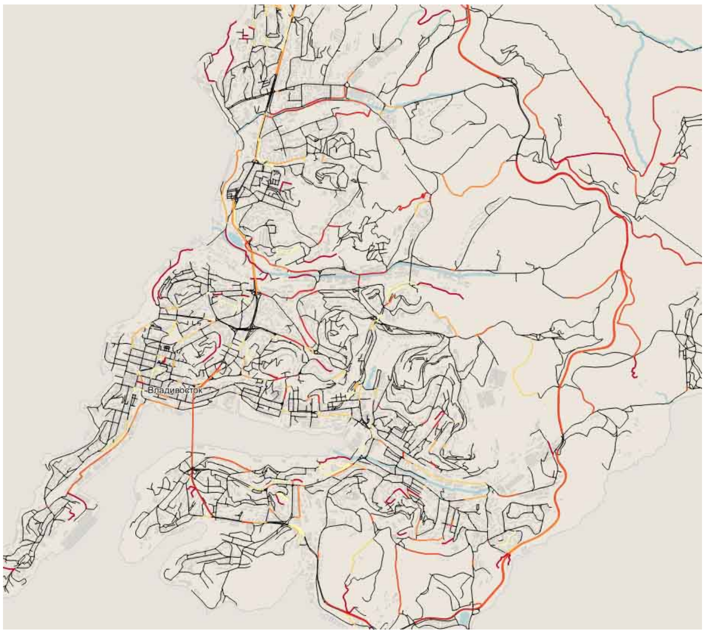

Fig. 4. Results of the vulnerability link detection with color gradient

The result of this algorithm is more consistent with expert assessment. It was found the central streets of the city and major transport interchanges. However, the resulting score is still far from perfect.

4 Conclusions

On the basis of network vulnerability research, the highway road network could be better planned and constructed, the network topology could be optimized and the most important nodes and links should be pay more attention to protect and operate. Complex network theory and graph theory are adopted to analyse and calculate the topological vulnerability of road network in Vladivostok city. To work with highway network as graph it was developed an information-computational system that allows to import data from OSM project in the spatial database and export it to graph edge list. On the process of vulnerability analysis and calculation, singly based on single metric is not accurate enough. Therefore, the problem of new structural vulnerability metrics developing is still important and up-to-date.

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