Robustness analysis of road networks

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Abstract. Damage events with difficulties to foresee are challenges to road networks especially under the background of a complex social environment. Robustness is critical in dealing with particularly high impact low chance events. In this paper the robustness of a road network is quantified to identify the weaknesses in the form of a road network. Theories of topology, structural vulnerability and road traffic are utilized in this paper. Transmittance of actual traffic flow is considered for the function evaluation of a network. This paper proves that the road networks has the weakness of single points or multi-point. If there is congestion, it may cause great functional loss to the local or the whole road network. Findings in this paper are strong supportive points of research for the propagation of more delicate-designed and form-improved road networks in urban areas. Adaption of the current work can be made when various practical cases are involved.

1. Introduction

It is generally accepted for road networks to deliver a reduced level of service in terms of total/average travel time or destination accessibility due to interruption events such as traffic congestion and accidents, infrastructure maintenance works or even strike. Other threats with lower frequency occurrence that can cause parts of road networks incompetence include severe weather, natural disasters or targeted attacks. High profile events have brought enormous attention to the research on disruption to transport networks such as the airline network disrupted by the 2010 volcanic ash cloud in Iceland [1], road and railway networks submerged by the floods in Columbia in 2011[2]and Canada in 2013[3].

The concept of robustness is defined as: “A road network is robust if damage to a large part of the network results in the failure of a small part or whole of it.” The concept is concerned with the disproportionateness of the consequences in relation to the damage [4]and it was firstly applied to structural systems [5].

2. Topology and function of road networks

2.1. Graphs of road networks
A road network can be represented by a set of edges (i.e. a link of two directions or an arc of one direction) connected at vertices in a graph model. Defined in [6], a road network is formed by a set of road circuits. A road circuit is a closed road route that provides two non-overlapped paths between a pair of vertices. The origin and destination of a circuit are the same (i.e. traffic leaves and returns to the same origin) but without visiting any other node more than once. A basic road circuit and its environmental area is the smallest functional unit of an operating road network.
2.2. Forms of road networks
As both are physical systems, a direct analogy has been used between a structure and a road network in order to examine the relationship between cause and effect[6]. The two systems are both dynamically functional ones due to connectivity among their elements. It is the form of either system that determines the systematic response by a changing flow to a changing potential.

Well-formedness is a definition that describes the quality of the form of a network system. A well-formed road network can provide stable and flexible services to its users such that trips can be made in any arbitrary direction i.e. from any vertex to any other within expected or accepted time.

A concept of continuance is a basis for the development of a measure of the well-formedness of a road network. Continuance was developed through traffic modulus (K) from an analogy with Young’s modulus in structural mechanics[6]. Defined as traffic flow over traffic strain, traffic modulus describes the relationship between actual traffic flow and actual travel time in the system dynamic terms. Combined with the fundamental relationship between flow and travel time defined in traffic flow theory, the continuance of a road lane is defined as in Equation 1.

\[
tr_l = \frac{Q}{(t_c - t_f)L}
\]

Where \(Q\) is capacity flow; \(t_c\) is actual travel time along the lane; \(t_f\) is the travel time for free uninterrupted flow; \(L\) is the lane length.

3. Form of road network elements

3.1. Well-formedness of a road location and a road circuit
Vertex well-formedness depends upon the continuance, orientations of intersecting links and functional characteristics of this vertex. Functional characteristics of a vertex may include 1) its type if it is a junction (e.g. roundabout, signal-controlled etc.); 2) its size if it is a location (e.g. population, number of stores, number of activities etc.); 3) its social utility (e.g. a hospital, a school, a police station etc.). Orientation of a link is reflected in a 2×2 matrix indicating the relative directionality of this link with respect to a defined co-ordinated system for the whole network. A link continuance matrix is the product of the continuance matrix of this link. The measure of vertex continuance is the determinant of the summation matrix of the continuance matrices of all the links.

3.2. Road clusters and clustering process
The clustering process for a road network begins by identifying all of the basic road circuits and calculating their well-formedness. Clusters are grown by including the neighbouring circuits so as to result in the most increase (or least decrease) in the well-formedness. When two clusters have the same well-formedness, the other four measures are maximised during the selection of candidate circuits in the order of priority.

A hierarchy model of a road network presents the clustering process starting from bottom to top. The higher the level the smaller is the number of clusters and the smaller amount of detailed information.

4. Unzipping of road networks

4.1. Failure scenarios of road networks
A failure scenario includes a series of damage events in which some vertices are disconnected from others in the circuit. Locations of damage events may result in consequences which vary from little i.e. reference nodes are still connected to each other and the well-formedness of the paths between them is not greatly damaged to extreme i.e. all of the nodes are separated from each other. Two of the essential aspects of consequences are separateness and loss of function. Separateness (S) is defined as a ratio of the loss in cluster well-formedness to the well-formedness of the intact network. Damage to connectivity among reference nodes is reflected by loss of Function (F).
The unzipping process searching for failure scenarios starts from the top of the hierarchy and ends in the bottom. Each cluster at each level in the hierarchy is damaged by the separation of its sub-clusters. Each separation consists of a set of links that are identified one by one referring to the unzipping criteria. Those links form a candidate failure scenario.

Figure 1 shows the network and its hierarchical model. Vertices 1 and 16 are reference nodes. Damage demand of each link in the network is identical as 69.04 and each link contains two lanes of opposite directions. The function value for each reference node (Vertex 1 and Vertex 10) is 10 and for the rest vertices the function values are identical as 1. Well-formedness for Circuit 1 to Circuits 9 is shown in Figure 1 (a).

Assume that 100 vehicles per hour are flowing from the origin, Vertex 1 to the destination, Vertex 10. The flow in this network is assigned in equilibrium as presented in Figure 1(b). Assume that the capacity of each link is 80 veh/hour.

The maximum failure scenario is Scenario a-15, i.e. the damage to link 1–2 in Table 1. The scenario is neither a total failure nor a partial failure. Since the network is symmetric horizontally, vertically and diagonally, it is apparent that there are four maximum failure scenarios, besides link 1–2, damage to link 1–5, link 12–16 and link 15–16 are the other three maximum failure scenarios respectively. Common features of the four failure scenarios are firstly, they have the smallest damage demand therefore these four failure scenarios are also minimum damage demand scenarios. Secondly the connectivity between two reference nodes and one reference node with other vertices is half damaged, i.e. one reference node
is half separated from other vertices since one of the two paths connecting a reference node to the rest of the network is damaged in the failure scenarios.

Scenarios containing one of the four links (link 1–2, 1–5, 12–16 and 15–16) have large consequences, for example Scenario a-1, a-2, b-1, b-2, b-3, b-124. However relative damage demand is different for these scenarios. It can be concluded that links directly connecting reference nodes especially those with relatively high function values play critical roles in network robustness. Damage to links connecting reference nodes would either lead to great separation or large function loss of the whole network.

5. Conclusions
- The vulnerability analysis for a road network is a method to evaluate the performance of the network experiencing damage events. It is the consequence and effort to cause damage events rather than the nature of those events that are measured in the analysis. The analysis is adapted from the structural vulnerability theory and is firstly applied in [6]. In this paper the analysis takes functions of a road network into account.
- Failure scenarios with high robustness indices identified in the unzipping process may cause the change of traffic flow on other links. Traffic congestion on other links, in a short time can be seen as damage events thus additional links should also be included in the failure scenarios. The road network may be in partial failure under these failure scenarios. Traffic flow re-distribution over the damaged network helps to generate failure scenarios under everyday traffic conditions. In future work the complexity of traffic flow on a road network is taken into consideration and traffic simulation methods should be used during traffic distribution processes.
- The analysis results in scenarios that may help designers and engineers identify the most vulnerable parts of large road networks so that they can be redesigned, monitored or better maintained to increase robustness.

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