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Investigating transport network vulnerability by capacity weighted spectral analysis

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ABSTRACT

Transport networks operating at or near capacity are vulnerable to disruptions, so flow bottlenecks are potent sources of vulnerability. This paper presents an efficient method for finding transport network cuts, which may constitute such bottlenecks. Methods for assessing network vulnerability found in the literature require origin-destination demands and path assignment. However, in transport network planning and design, demand information is often missing, out of date, partial or inaccurate. Capacity weighted spectral partitioning is proposed to identify potential flow bottlenecks in the network, without reference to demand information or path assignments. This method identifies the network cut with least capacity, taking into account the relative sizes of the sub-networks either side of the cut. Spectral analysis has the added advantage of tractability, even for large networks, as shown by numerical examples for a five-node illustrative example, the Sioux Falls road network and the Gifu Prefecture road network.

1. Introduction

Transport networks differ greatly in their vulnerability to disruptions. The presence and location of flow bottlenecks will be an important factor determining transport network vulnerability. There is extensive literature on methodologies for assessing transport network vulnerability using concepts like reserve capacity, which require estimates of demand and path assignment. The approach taken here is to identify potential network bottlenecks without reference to demand or path assignment, by looking for the network cut that offers the least normalized capacity, where a cut is defined as a set of links, which, when removed or disabled, would partition the network into two sub-networks. Normalization takes account of the position of the cut; a cut through the centre of the network will, in general, offer more capacity than a cut separating a small peripheral sub-network from the main body of the network, so normalisation gives priority to more central cuts when identifying the cut with least capacity.

The proposed spectral partitioning approach to bottleneck identification is related to the concept of network reserve capacity (Wong and Yang, 1997; Yang et al., 2000; Kasikitwiwat and Chen, 2005), but does not require any knowledge of the underlying origin-destination matrix, paths or path assignment. It is also closely related to the maximum flow problem of operations research (Boffey, 1982), but does not require the identification of origins and destinations.

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2. Contribution

The central contribution of this paper is to show how spectral analysis, based on the graph Laplacian derived from the capacity weighted adjacency matrix, can be used to identify potential bottlenecks in large transport networks efficiently and without demand information. It is shown that spectral partitioning solves a relaxed but much more tractable set partitioning problem. The derivation of the partitioning method presented here leads to an improved upper bound for the second smallest eigen value of the graph Laplacian than Cheeger's inequality, thereby more closely relating the capacity of the network cut to the second smallest eigen value of the graph Laplacian.

Verification of the partitioning method is achieved by applying it, firstly to a five-node illustrative example, then to the Sioux Falls road network, and finally to the Gifu Prefecture road network. It is thus demonstrated that capacity weighted spectral analysis provides transport planners and network designers with a quick and easy way to identify potential flow bottlenecks in transport networks, without the need for data on origin-destination demands or path assignments. Spectral analysis has been widely applied to many kinds of network (see the following literature review), but this is believed to be the first application of the technique for the identification of flow bottlenecks in transport networks. As spectral analysis is tractable for large networks, it is useful in transport network planning and design, when there is a need to ensure that the network offers sufficient flow capacity.

3. Literature review

3.1. Transport network vulnerability

Vulnerability is the susceptibility of the transport system to incidents causing operational degradation (Berdica, 2002; Faturechi and Miller-Hooks, 2015). Vulnerability analysis facilitates pre-disaster mitigation planning in the disaster management cycle, and is one of several key performance measures used in the literature for evaluating and analyzing the impacts of disasters (Faturechi and Miller-Hooks, 2015). It assesses the reduction of network accessibility as a consequence of failure, with a view to identifying the critical components in the network (Bell, 2000; Jenelius et al., 2006; Taylor et al., 2006; Chen et al., 2007; Murray and Grubesic, 2007; Bell et al., 2008; Kurauchi et al., 2009; Nagurney and Qiang, 2010; Luathep et al., 2011; Chen et al., 2012; Taylor and Susilawati, 2012). The results of vulnerability analysis can also be employed for pre-disaster network design.

Transport network vulnerability and the related concepts of reliability, robustness and resilience have attracted growing academic attention, as evidenced by a number of recent special issues, most notably "Resilience of Networks" in *Transportation Research Part A* (Caschili, Medda, et al., 2015), "Resilience and Vulnerability of Spatial Economic Networks" in *Networks and Spatial Economics* (Caschili, Reggiani, et al., 2015), and "Quantitative Approaches to Resilience in Transportation Networks" in *Transportmetrica A* (Chow et al., 2015). These special issues address the importance of exploring the vulnerability of transport systems, which are impacted by natural and man-made disasters or disruptions with increasing complexity and intensity in recent years. Several recent reviews have been conducted on the modelling of vulnerability and resilience of transport infrastructure and networks. Mattsson and Jenelius (2015) categorized vulnerability analysis into two types; system vulnerability analysis and topological vulnerability analysis. System vulnerability analysis considers the demand and supply side of transportation systems to quantify the consequences of disruptions or interruptions for road users. Various kinds of traffic assignment model have been used to determine network equilibrium traffic flows, travel times, alternative routes, and socio-economic impacts (Wang et al., 2015). In contrast, the studies of topological vulnerability make use of graph theory to analyze the vulnerability of transport networks based on their topological properties and indicators, such as connectivity, degree centrality and betweenness centrality (Demšar et al., 2008; Kurauchi et al., 2009; Duan and Li, 2014). This study belongs to the category of topological vulnerability analysis.

Previous studies on the vulnerability of transport networks generally aim to identify the links or nodes, which when removed diminish the accessibility of the network most. The traditional approach to measuring network vulnerability adopts the full network scan method. To evaluate the consequence of the failure of a link, each link is removed from the network and the traffic assignment problem is solved each time. This approach is computationally demanding for a complete vulnerability analysis of a large network. Attempts have been made to simplify the process by pre-selecting potentially vulnerable links using link-based indicators (Knoop et al., 2012), scanning for representative locations (Taylor and Susilawati, 2012), partial network scanning for the impact area of a link (Chen et al., 2012), and a sensitivity based approach to estimating the change of network accessibility with respect to link capacity degradation (Luathep et al., 2011). The objective of these studies is to improve the computational efficiency of vulnerability analysis in large networks and thereby identify the most vulnerable links with limited runs of an equilibrium assignment model.

3.2. Spectral analysis and clustering

An important problem that can be addressed efficiently by spectral analysis is the partitioning of a network based on a given common feature. When considering connectivity, this involves findings clusters of nodes, which have rich intra-cluster connections and poor inter-cluster connections. When such clusters do not overlap, their boundaries define the desired