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Vulnerability analysis for large-scale and congested road networks with demand uncertainty

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ABSTRACT

To assess the vulnerability of congested road networks, the commonly used full network scan approach is to evaluate all possible scenarios of link closure using a form of traffic assignment. This approach can be computationally burdensome and may not be viable for identifying the most critical links in large-scale networks. In this study, an "impact area" vulnerability analysis approach is proposed to evaluate the consequences of a link closure within its impact area instead of the whole network. The proposed approach can significantly reduce the search space for determining the most critical links in large-scale networks. In addition, a new vulnerability index is introduced to examine properly the consequences of a link closure. The effects of demand uncertainty and heterogeneous travellers' risk-taking behaviour are explicitly considered. Numerical results for two different road networks show that in practice the proposed approach is more efficient than traditional full scan approach for identifying the same set of critical links. Numerical results also demonstrate that both stochastic demand and travellers' risk-taking behaviour have significant impacts on network vulnerability analysis, especially under high network congestion and large demand variations. Ignoring their impacts can underestimate the consequences of link closures and misidentify the most critical links.

1. Introduction

Robust transportation networks have been regarded as one of the preconditions for a flourishing economy and a high quality of life. A transportation network, however, can be vulnerable to various natural and/or man-made disasters (or incidents). For instance, bridge collapses or terrorist attacks at major expressways can result in widespread service disabilities and cause considerable travel delays. Adverse weather such as heavy snow and flooding could severely degrade the network performance. Although the occurrence probability of these major incidents is low, their consequences could be sufficiently large to indicate a major problem that warrants remedial actions. Therefore, it is important to understand the potential vulnerability of transportation networks to such major incidents, so as to manage their risks and hence better alleviate resulting disruptions to all aspects of urban and rural life.

A key issue in the vulnerability analysis is to identify the critical infrastructures (links/nodes) of a network, where the failure of those infrastructures would have the most serious impacts on the whole network. After identifying the critical infrastructures, the network robustness can be enhanced through reinforcing these identified critical infrastructures or constructing new alternative parallel paths (Matisziw and Murray, 2009).

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A commonly used technique in the literature for identifying critical links is the full network scan approach (Jenelius et al., 2006; Taylor et al., 2006). In this approach, each link is iteratively removed from the network and the consequences of its closure are measured in terms of the reduced network performance. The critical links are then identified by evaluating all possible link closures. To reduce the computational burden, it is generally assumed that the link travel times are independent of traffic loads (Kurauchi et al., 2009; Jenelius et al., 2006). This assumption is quite reasonable for the network with a low travel demand, while it may not be valid for the congested road networks (Berdica and Mattsson, 2007; Knoop et al., 2008). For this case, it is necessary to apply traffic assignment models to account for the congestion effects and traveller responses to the link closures (Chen et al., 2007; Taylor, 2008).

However, incorporating a full network scan approach with traffic assignments can be computationally intensive. For example, the well-known Chicago regional network for testing traffic assignment algorithms consists of 39,018 links. For each link closure, a traffic assignment conducted on the Chicago regional network requires about a half hour (to achieve 10^{-4} relative gap) (Dial, 2006). Consequently, the full scan approach can take about 2 years to identify most critical links in such network. Thus, this full network scan approach may not be viable for critical link identification in large-scale congested road networks.

In order to further reduce the computational burden associated with the full network scan approach, D'Este and Taylor (2003) and Taylor and D'Este (2004) pre-select potential vulnerable links based on certain strategies and only conduct analysis on these pre-selected links. The potential vulnerable links can either be part of a minimum cost path between O–D nodes, or the links with high choice probabilities, calculated by the stochastic traffic assignment. Based on the similar ideas, Knoop et al. (2007) tested nine different link-based strategies (e.g. volume/capacity ratio) for selecting potential vulnerable links. They found that none of these strategies was good enough to properly identify the critical links on a congested road network.

Modelling travellers' behavioural responses to link failure is another key issue involved in critical link identification. Demand variations due to link closure have been well evidenced in many empirical studies, such as recent bridge collapse in Minnespolis, United States on 1st August 2007 (Danczyk and Liu, 2010). Under such a situation, the high degree of demand uncertainty will inevitably yield travel time variability, and consequently imposes additional disutility on travellers. Many empirical studies have revealed the significant influence of travel time uncertainty on travellers' route choice behaviour (Lam and Small, 2001; Tam et al., 2008; Wu and Nie, 2011). Travellers under travel time uncertainty tend to choose reliable shortest path, not only dependent on travel time saving, but also on reduction of travel time variability. This risk-taking behaviour under demand and travel time uncertainty have received considerable attention in the transportation network reliability analysis (Shao et al., 2006; Lo et al., 2006; Siu and Lo, 2008). However, such demand variations and associated travellers' risk-taking behaviour due to link closures have not yet been considered in the studies of critical link identification.

In view of the above, this study proposes an efficient ''impact area'' vulnerability analysis approach for identifying the most critical links in large-scale and congested road networks with demand variations. The proposed approach evaluates the consequences of a link closure within its local impact area instead of the whole network. This impact area vulnerability analysis is based on the empirical findings that the closure of a link would have serious impacts mainly on its adjacent links and nodes within the local impact area. As the local impact area is relatively small, computational times required for assessing the consequences of all possible link closures within the impact area, are moderate. With this approach, the computational performance required by the critical link identification can be dramatically reduced.

In addition, the effects of demand variations and travellers' heterogeneous risk-taking behaviour on the vulnerability analysis are investigated in this study. A new vulnerability index is introduced to evaluate the consequences of a link closure with consideration of their effects. It is found in this study that both demand variations and travellers' risk-taking behaviour have significant impacts on network vulnerability, and ignoring their impacts could underestimate the consequences of link closures and misidentify the most critical links.

The remainder of this paper is organized as follows. In the next section, the reliability-based traffic assignment model and the definition of demand variations are briefly described. It follows with the definition of vulnerability index for accessing the consequences of a link closure in congested road network in Section 3. The impact area vulnerability analysis approach is then presented in Section 4. Numerical examples of a medium-scale and a large-scale road network are presented in Section 5. Finally, the conclusions are given in Section 6, together with future research directions.

2. Reliability-based user equilibrium model and demand uncertainty

In this paper, the reliability-based user equilibrium (RUE) model proposed by Shao et al. (2006) is adopted for modelling the travellers' heterogeneous risk-taking behaviour on congested road network with demand variations arising from major incidents. For completeness, the concepts of demand variations and the RUE model is brief described in this section. Note that the supply uncertainty is not considered in this paper, since it is not applicable to the scenarios with pre-defined link closure for critical link identification. For notational consistency, capital letters represent random variables and lower-case letters represent deterministic variables. A list of notations can be found in Appendix A.

Consider a road network represented by a strongly connected graph $G = (N,A)$, where N and A are the sets of nodes and links respectively. RS denotes the set of Origin–Destination (O–D) nodes, where node $r \in N$ is the origin and node $s \in N$ is the