Journal of Transport Geography 39 (2014) 145–155

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Measuring vulnerability of road network considering the extent of serviceability of critical road links in urban areas

Chandra Balijepalli *, Olivia Oppong

Institute for Transport Studies, University of Leeds, Leeds LS2 9JT, England, UK

ARTICLE INFO

Keywords:
Vulnerability
Degraded network
Serviceability
Emergency response plan
Traffic diversion plan
Traffic network modelling

ABSTRACT

Road networks are vulnerable to natural disasters such as floods, earthquakes and forest fires which can adversely affect the travel on the network that remains intact after an event. However, not all road links equally affect the travel conditions in a given network; typically some links are more critical to the network functioning than the others. It is noted that the majority of the existing indices designed to measure vulnerability offer a good measure of network-wide accessibility in sparse regional networks, but they rarely consider the extent of serviceability of critical links in dense urban road networks. This paper describes a number of vulnerability indices from the literature, applies them to the case of urban network of York and discusses the results. It proposes a new vulnerability index considering the serviceability of road links and illustrates its computation. Finally, this paper uses the results of the new vulnerability index and outlines a traffic diversion plan in the event of flooding in York using traffic network modelling techniques combined with Geographic Information Systems (GIS) application.

1. Introduction

Road networks are vulnerable to natural disasters such as floods, earthquakes and forest fires which can cause immense damage to the infrastructure resulting in adversely affected travel on the degraded network. Typically after the occurrence of an event some places become less accessible e.g. following a bridge collapse due to an earthquake in Kobe (Chang and Nojima, 2001), structural damage after an earthquake in Haiti in 2010 (Bono and Gutierrez, 2011) or after a heavy snow fall or even during/after a forest fire. Studying and analysing vulnerability of road networks will help in prioritising the planning, budgeting and maintenance of roads and also will be useful in preparing emergency response plans.

It is noted, however, that not all road links of a network are equally critical to its functioning, that is, to say, some links have a greater impact on network flows than the rest. Therefore it is very important to analyse the vulnerability of a network considering the importance of the roads within. The importance of analysing vulnerability caught the attention of researchers especially in the past 6–10 years due to an evident increase in the frequency of natural disasters over the past decade or so (Taylor et al., 2006). There is a good volume of literature available on the vulnerability of road networks with some valuable research methods described. Some of the methods developed were based on accessibility measures (Taylor et al., 2006) which analysed the vulnerability in sparse regional networks. Some others have been based on network topological measures e.g. Latora and Marchiori (2001). Then there are methods which consider the importance of the links and analyse the impact of complete disconnection (Jenelius et al., 2006) and the consequences of geographical disparities (Jenelius, 2009). Whatever the approach, all methods focus on accessibility in sparse networks and rely on considering complete link failures to arrive at an indication of the vulnerability of the network. In contrast, we are interested in studying the vulnerability of dense urban road networks which pose new challenges as accessibility alone may not be the central issue anymore (due to a large number of alternative routes being available), but it is the importance of the road link to the functioning of the network that will need greater attention. Moreover, in real life situations, after an event, roads may not always become completely unusable, but they may still be partially available for use. This then raises several questions – (i) whether the indices developed in the past are indeed suitable to the context of denser urban networks; (ii) if so do they consider the importance of the road links within; and, finally (iii) do they allow for analysing partially available roads as against completely damaged ones?

In this paper, firstly, we set out to investigate the indices known from the literature and aim to answer the questions raised. Secondly, we introduce a new measure to analyse the vulnerability of a road network considering the importance of the roads. Road

* Corresponding author.
E-mail addresses: N.C.Balijepalli@leeds.ac.uk (C. Balijepalli), ts12o2o@leeds.ac.uk (O. Oppong).

http://dx.doi.org/10.1016/j.jtrangeo.2014.06.025
0966-6923/

networks usually follow a scheme of hierarchy e.g. Motorways, A-roads, B-roads and C-roads in England (DfT, 2012a) based on the significance of their functioning and in this paper we aim to capture the importance of the roads based on their hierarchy. We also aim to make the new measure flexible enough to consider both partially and fully damaged roads. This allows the new vulnerability measure applicable in practical real life situations and it also allows for many possible 'what-if' scenarios to be built and tested.

Studying and analysing vulnerability will help in developing the mitigating measures. The analysis of vulnerability has far wider applications such as in planning and maintaining road networks, prioritising and budgeting, preparing for emergency response (Walker et al., 2004). In this paper, as an example, we develop an outline plan to divert traffic in case of an urban network under flooding. The diversion plan prepared uses traffic assignment modelling technique together with Geographic Information System (GIS) and is aimed at maintaining connectivity as well as minimising the travel time on the degraded network.

This paper is set out in six sections including this one. Section 2 reviews the literature identifying the relevant approaches to analysing vulnerability of road networks. Section 3 introduces the new measure of vulnerability. Section 4 describes the case of York introducing the geography and flood prone roads in York. Section 4 also describes the steps involved in computing the vulnerability indices. Section 5 illustrates the indices and analyses the consequences of road failures. Section 5 also outlines a traffic diversion plan aimed at maintaining connectivity during floods as well as minimising the travel time on the degraded network. Section 6 concludes the research work reported in this paper.

2. Literature review

This section defines the term vulnerability and then presents an overview of the network vulnerability indices before specifying them with mathematical notation in the later part of the section.

2.1. Definition of vulnerability, serviceability and criticality

Many authors suggest that there is no single definition suitable for vulnerability but it must be defined in the context of an event (Jenelius et al., 2006; Einarsson and Rausand, 1998; Holmgren, 2004; Berdica, 2002). Laurentius (1994) described vulnerability as "*susceptibility for rare, big risks*" while Holmgren (2004) defined it as "*sensitivity to threats and hazards*".

The term *risk* can be considered as containing two components – the probability of an event occurring and the consequences arising due to the event (Berdica, 2002). It is well known that the probabilities are difficult to estimate as they are based on historic information which assumes the circumstances around an event remain the same at all times. On the other hand it is very important to be able to assess the consequences of an event as they affect daily life, business and economy. In this paper we aim to focus on the consequences rather than the probabilities.

Taylor et al. (2006) considered the vulnerability from the point of view of reduced accessibility, which is very similar to the definition followed by Jenelius et al. (2006). In this paper we follow the definition of Berdica (2002), "*vulnerability as the susceptibility to incidents that can result in considerable reductions in road network serviceability*" which has been widely used since then. Berdica (2002) also defines similar term *robustness* as the "*ability to cope with disturbing incidents*" which relates to the term vulnerability by definition, i.e. a network which is less robust is considered as more vulnerable. Furthermore, *serviceability* of a link is defined as the *possibility to use that link during a given period* which then relates to the possibility of partial degradation of roads. Finally, if the consequences of a link being affected are great then the link is considered *critical* to the network.

Based on the definitions, a number of vulnerability measures have been developed which are outlined in the next few paragraphs.

2.2. Specification of vulnerability indices

This section specifies a series of indicators to measure the vulnerability of road network, to facilitate investigating their suitability in case of an urban network set out in a later section.

The literature on vulnerability indices can be broadly grouped into the distance-based and the cost-based approaches. Indices based on travel distance are relevant to sparse regional networks where if a link is blocked drivers may need to take longer detours to reach their destinations. On the contrary, in dense urban networks usually several alternative routes are available, and moreover, it is well known that drivers often prefer quicker routes which need not necessarily be shorter in distance terms. Hence the indices such as Hansen's Index (Taylor et al., 2006) and the Efficiency Measure (Latora and Marchiori, 2001) which are based purely on distance are considered unsuitable for measuring vulnerability of dense urban road networks and for this reason we omit them from further discussion in this paper.

Now, consider a network of links serving Origin–Destination (OD) demand represented by $Q = \{\ldots, q_k, \ldots\}$ where q_k is the demand for a particular OD pair k. Let A be the set of links indexed $a = 1,2,\ldots A$. The link travel times $\mathbf{t}$ are assumed to be function of link flows. Thus if x_a denotes the flow on link a ($a = 1,2,\ldots A$) with $\mathbf{x}$ the A-vector of flows across all links, then the travel time t on link a is denoted $t_a(\mathbf{x})$. Let N be the number of nodes on the network. With this basic notation we now specify the measures of vulnerability as defined by various authors.

2.2.1. Travel cost-based vulnerability measures

M1: Change in generalised cost measure (Taylor et al., 2006)

The generalised cost, a measure of disutility of travel usually measured in terms of a combination of distance travelled and time spent, is used as a measure of accessibility. The index T_a measures the change in generalised cost between when a link is intact and when the link is removed and is defined as follows;

$$T_a = \sum_k q_k \Delta c_{ka} \tag{1}$$

where $\Delta c_{ka} = c_k - \tilde{c}_{ka}$ change in generalised cost for OD pair k when link a fails, c_k the least path cost for OD pair k, $\tilde{c}_{ka}$ is the least path cost for OD pair k when link a has failed.

M2: Network efficiency measure (Nagurney and Qiang, 2007)

The Nagurney and Qiang transportation network efficiency measure $\varepsilon(G,Q)$ for a given network of topology G and origin destination demand Q is defined as

$$\varepsilon(G, Q) = \sum_k \frac{q_k}{c_k} / n_k \tag{2}$$

where n_k is the number of OD pairs.

Eq. (2) represents the average number of trips per unit cost and represents the efficiency of the network in terms of traffic to cost ratio. The higher the traffic handled per unit cost, the more efficient the network is.

M3: The importance measure (Jenelius et al., 2006)

The importance measure assumes that all drivers are forced on a more expensive route when an event causes the disruption or closure of a link or a group of links. Their behaviour is described by the user equilibrium principle where the route choice is meant to minimise personal travel cost. Following from (1) the basis for