JOURNAL OF TRANSPORTATION
SYSTEMS ENGINEERING AND INFORMATION TECHNOLOGY
Volume 13, Issue 5, October 2013
Online English edition of the Chinese language journal

Cite this article as: J Transpn Sys Eng & IT, 2013, 13(5), 79−85.

RESEARCH PAPER

Traffic Incident Situation Evaluation Based on Road Network Reliability of Invulnerability

ZHAO Xinyong[1, 2], AN Shi[* 1], CONG Haozhe[2]

1 School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China
2 Road Traffic Safety Research Center of the Ministry of Public Security, Beijing, 100062, China

Abstract: To comprehend and evaluate the severity of traffic incident situations, an unconventional traffic management strategy should measure and calculate the severity of incident situations. This paper presents a freeway network traffic incident situation evaluation model by introducing the invulnerability concept in the complex network theory and perceiving the topological structure of a road network with the help of traffic incident situations. A case analysis was conducted for the invulnerability of a regional freeway network subsystem and the overall network. The model provides a solution for incident situation comprehension from the road network structure point of view.

Key Words: intelligent transportation; road network reliability; road network reliability of invulnerability; traffic incident situation; situation evaluation

1 Introduction

A regional road network consists of key nodes and sensitive sections that vary in road capacity, road network structure, traffic flow, and road environment. Traffic incidents such as special events frequently occur in these road network locations. Traffic incidents degrade the road network performance. Therefore it is important for traffic management personnel to measure and a road network's ability for responding to incidents and to evaluate the severity of incidents.

Network reliability was studied first in the field of communication networks, water supply networks, and electricity supply network. Transportation network reliability research started later. In 1991, Asakura and Kashiwadani[1] examined the reliability of road networks in traffic fluctuations. In 1997, Bell and Iida[2] pointed out that the biggest difference in reliability studies of road networks and other networks was that the former needs to consider the route choice behaviors of travelers. Over the last two decades, road network reliability studies mainly involve the following three aspects: connectivity [2], travel time [3], and transport capacity [4, 5]. The research method is mainly classified into two categories: one is the analysis of the entire road network reliability based on sectional analysis [4–7], the other is using Game Theory to evaluate the operation of the entire road network. For example, Bell [8] used Game Theory to conduct the road network reliability assessment and then proposed that even when the road network running status is extremely pessimistic, the road network is considered reliable if the travel cost is acceptable. Du and Nicholson defined reliability in the case when transport capacity decreases. Berdica [10] introduced invulnerability to measure the weak links of a road network and their influence. Tarlor [11] used the road network's density model to study the reliability of the road network, the permeability, accessibility, and flexuosity to evaluate the layout of the road network and the traffic management schemes. Tarlor's study focused on a local area network. Liang and Chen [6, 7] presented the unimpeded reliability of road sections and intersections for the evaluation of a road network's operating status. Although this method considered the traffic flow on the sections, it ignored the travelers' route choice behaviors.

In summary, the earlier studies on transportation network reliability have made good progress in several aspects. Many relative definitions and indicators were put forward. However, most research was carried out with a particular focus on one

Received date: Mar 12, 2013; Revised date: May 15, 2013; Accepted date: May 20, 2013
*Corresponding author. E-mail: anshi@hit.edu.cn

DOI: 10.1016/S1570-6672(13)60125-7

aspect of the transportation network with its effectiveness as the main goal. In fact, the reliability of complex networks should be considered from three aspects: survivability, invulnerability, and effectiveness. A road network and a road network subsystem are composed of nodes and links. In a highway network, the nodes generally include some important facilities such as intersections, service areas, toll stations, entrance ramps, while the links usually refer to the basic roads. At the network level, when the system breaks down due to incidents, the reliability metrics should be considered in two aspects. First, a subsystem failure will directly affect the flow of traffic between some ODs resulting in some traffic being unable to traverse the original path. Therefore, the amount of affected traffic can be used as a measurement of the subsystem reliability. Secondly, the amount of traffic which is unable to traverse the original path must use other paths, resulting in re-distribution of the traffic flow in the network. Whether the affected traffic can be absorbed by the residual network can also reflect on the degree of coordination between the structure of the section network and the traffic's emergency demand, as well as its level of difficulty to accomplish it.

This paper introduces the invulnerability concept using the complex network theory. On the basis of the topology of the road network, a model was established based on the road network invulnerability to recognize emergencies on the freeway. Moreover, this paper used real-case scenarios to analyze the survivability of the highway network' subsystem and the overall network, which enhances the understanding of the proposed concept from the perspective of the road network structure.

2 Model for understanding network events based on road network invulnerability

Using the aforementioned concept, the Incident Network Invulnerability (INI) is defined as the reliability of the traffic. The value of the INI ranges from 0 to 1. INI=1 indicates 100% reliable, and on this condition the failure of the node does not affect traffic; INI=0 indicates a subsystem or network failure, indicating that the traffic flow on the whole road network is abnormal. The closer the INI value to 1, indicates that the node is more reliable. On the contrary, the closer the INI to 0, the node is more likely to fail. The Incident Network Invulnerability can be used to characterize the road network's ability in order to meet the traffic demand and respond to emergencies.

2.1 Nomenclatures

Q: the demand matrix of OD;

E: the set of links, the link is the line between two nodes, $|E|=m$;

V: the set of nodes, $|V|=n$;

P: the set of effective roads, $|P|=k$;

D: the vector about the traffic flows on effective roads, $\boldsymbol{D}=(d_1,\cdots,d_k)$, d_i is the traffic flows on the i-th effective road, the unit can be changed according to specific scenarios, such as Veh, Ton, or Number of people.

$H_{k\times m}$: the associated matrix of effective roads

$$\mathrm{h}_{ij}=\begin{cases}1 & \text{the } j\text{-th side is on the } \mathrm{i_{th}} \text{ effective road}\\ 0 & \text{else}\end{cases}$$

$$i=1,2,\cdots,k, j=1,2,\cdots,m;$$

$Z_{k\times n}$: the associated matrix of the shortest roads

$$\mathrm{z}_{il}=\begin{cases}1 & \text{the } l\text{-th node is on the ith effective road}\\ 0 & \text{else}\end{cases},$$

$$i=1,2,\cdots k, l=1,2,\cdots,n;$$

τ : the Incident Network Invulnerability

f : the subsystem or subsystem set's vulnerable coefficient, which represents the ratio of the affected subsystem (set) isolated from the road network traffic and the total traffic;

$\boldsymbol{U}=\boldsymbol{H}^T\bullet\boldsymbol{D}$: the vector about the traffic flows on the links, $\boldsymbol{H}^T$ is the transpose of ***H;***

$\boldsymbol{W}=\boldsymbol{Z}^T\bullet\boldsymbol{D}$: the vector about the traffic flows on the nodes, $\boldsymbol{Z}^T$ is the transpose of ***Z;***

Ω: the affected area after the destruction of a link or a node, that is the set of links which stop running because of the failure of the link or the node. The loss of a subsystem's failure can be divided into two types, the direct loss and the indirect loss. Direct loss refers to the failure of this subsystem while the indirect loss refers to the failure of other subsystems due to the failure of this subsystem. But the increase of the traffic flow on the node subsystem and the link subsystem may cause double-counting of traffic. Above all, we can simply let the affected links set be the affected range of this subsystem, which can be used for calculating the Incident Network Invulnerability.

2.2 Subsystem's invulnerability model

The associated matrix of the effective roads consists of 0 and 1. This paper introduces the logic computing, represented by OR. The rule is: OR(0, 0)=0; OR(0, 1)=OR(1, 0)=1; OR(1, 1)=1. So the rule of the matrix is: the dimension of matrix ***S*** and ***T*** is $m\times n$, then:

$$[OR(S_{m\times n},T_{m\times n})]_{ij}=OR(s_{ij},t_{ij})$$

The continuous operation symbol based on logic OR is $\sum^{\mathrm{OR}}$, for example:

$$\sum_{i=1}^{3}{}^{\mathrm{OR}}\ \boldsymbol{S}_i=\mathrm{OR}(\boldsymbol{S}_1,\boldsymbol{S}_2,\boldsymbol{S}_3)$$

The invulnerability of the subsystem, which is denoted as l, can be defined as:

$$\tau_l=1-f_l=1-\frac{D\cdot\sum_{x\in\Omega_j}{}^{OR}H_x}{\sum_{i=1}^{n}\sum_{j=1}^{n}q_{ij}},\quad l=1,2,\cdots,n$$

where H_x: the x th column vector of the matrix ***H***;

Ω_l : the links that cannot work well when subsystem l is