IDENTIFYING CRITICAL INFRASTRUCTURES IN A ROAD NETWORK BASED ON EMERGENCY RESPONSE ACCESSIBILITY

Afshin Shariat Mohaymany¹, Navid Kalantari², Mahmoud Mesbah³, Poria Mohammadian⁴

ABSTRACT

Transportation networks play an important role in search and rescue action after an earthquake; therefore, it is necessary to keep the transportation network reliability as an essential lifeline at an acceptable level with respect to the expected performance of the network after an earthquake. Providing accessibility and transportation network ability to satisfy the post-earthquake demand are two of the most important measures of performance; hence, this article first uses a Time-Space accessibility measure that is based on the expected performance of the network after an earthquake, then a method for identifying critical infrastructures in a road network is presented by using the upper bound and lower bound method for estimating accessibility reliability with respect to damage probability of the network components. This method could be used for road transportation network assessment.

Keywords: emergency response, network assessment, earthquake, reliability, accessibility

INTRODUCTION

Today natural disasters endanger people’s lives. After the occurrence of a disaster one of the major efforts is the search and rescue actions that take place in the initial hours, transportation plays a crucial role in all the activities associated with these actions.

All over the world different natural disasters causes damages to road transportation networks. Natural disasters such as; earthquakes, hurricanes, floods and etc. are some of the major incident that may impulse damages to the network. Some of the events in the past have shown that road networks are one of the most vulnerable transportation facilities in these incident.

One of the first steps in analyzing the road transportation network’s performance in different incident is to define different performance measures for the road network. One of these performance measures that have been used by many researchers is the travel time in the network. Travel time is a very important measure that largely affects the functionality of the network after an event. Shinozuka et al. (2001) has used the total delay induced by an earthquake to evaluate the seismic risk of highway networks. Loh et al. (2004) have also used this measure to evaluate the seismic risk of the Taipei region. Nojima and Sugito (2000) have considered the traffic flow of each link in the network, travel time, travel length and total travel time for post earthquake transportation system evaluation.

¹ Assistant Professor, College of Civil Eng, Iran University of Science and Tech, Tehran, Iran, Email: Shariat@iust.ac.ir
² MS, College of Civil Eng, Iran University of Science and Tech, Tehran, Iran, Email: Navid_kalantari@civileng.iust.ac.ir
³ MS, College of Civil Eng, Iran University of Science and Tech, Tehran, Iran, Email: Mesbah@iust.ac.ir
⁴ MS, College of Civil Eng, Iran University of Science and Tech, Tehran, Iran, Email: P_mohammadian@civileng.iust.ac.ir
Another performance measure that has been widely used by researchers is the cost of the network. The costs of transportation networks can be categorized in two different categories direct cost and indirect cost of the network damages. The direct cost of the network are those caused by physical damages of the network components such as; bridge, tunnel and road embankments. Indirect costs are the economic losses that have been induced by traffic delays and etc. researchers such as Kiremidjian et al. (2001), Warner (2001), Dalziell and Nicolson (2001) and Gordon et al. (1998) have used the cost or economic direct and indirect cost of the network for evaluation of the network risk and its performance. Taylor and Glen (2004) have used the following equation to estimate the consumer surplus in Australians highway network and identified the critical link in the network:

\[ V_{rs} = \sum_i \sum_j d_{ij} \cdot v_{ijr} \cdot dV \]

Where:
- \( d_{ij} \): The travel demand of \( j \) to \( i \)
- \( v_{ijr} \): is the excess travel cost for traveling from \( i \) to \( j \) from link \( e_{rs} \)

Safety is another performance measure for transportation networks. A desirable transportation network is a network that would provide an acceptable level of safety for travelers. The quality of transportation is an important measure in incidents the way in which different commodities and road users are being transported has a significant effect on the systems performance. Reliability is also an important measure in transportation system performance; travel time reliability, connectivity reliability, capacity reliability and accessibility reliability are some of the most important factors that affect the transport system performance after an incident.

Capacity of a transportation network has also been investigated by some researchers such as Mahmassani and Murray-Tuite (2004) and the vulnerability of the network has been estimated by its capacity and existence of alternative routs in the network. Accessibility of a transportation network has been investigated be Change and Nojima (2001). They have measured the networks physical accessibility after an earthquake.

In this article accessibility has been used as the performance measure of the network. The emergency response accessibility of the network is the major consideration of this article and the risk index of transportation networks will be evaluated based on their emergency response accessibility. Other performance measures such as; capacity and travel time are also some how included in the accessibility measure.

**ACCESSIBILITY**

Based on the experiences that have been achieved in Iran’s recent earthquakes as mentioned before, after reviewing different type of accessibility measures the accessibility model presented by Kalantari (2006) has been used in this article, the model is shown in Eq. 2:

\[ A^{(k)} = \frac{\sum_{d=1}^{D} A_d^{(k)} D_d}{\sum_{d=1}^{D} D_d} \]

This measure is a time space accessibility measure were \( A_d^{(k)} \) is the accessibility of node \( d \) in the state \( k \) of the network, \( A_d^{(k)} \) is calculated by Eq. 3:
\[ A_d^{(k)} = \min \left[ \sum_{i=1}^{s} S_{ds} \times X_{ds} / \omega_d D_d, 1 \right] \]  

(3)

Where:
- \( S_{ds} \) is the rescue potential of node s to node d,
- \( X_{ds} \) is the travel time value of node s to node d,
- \( D_d \) is the total damage of node d,
- \( \omega_d \) is a factor related to the difficulty of rescue activities and the importance of node d.

\( X_{ds} \) has the following definition:

\[
X_{ds} = \begin{cases} 
    b_1 & \delta_{ds} \leq T_1 \\
    b_2 & T_1 \leq \delta_{ds} \leq T_2 \\
    \vdots & \\
    0 & T_n \leq \delta_{ds} \\
\end{cases}
\]

(4)

\( b_1, b_2, b_3, \ldots \leq 1 \)

\( b_1 > b_2 > b_3 > \ldots \)

Where \( \delta_{ji} \) is total rescue time from j to i, \( b_1, b_2, \ldots \) are the travel time value and \( T_1, T_2, \ldots, T_n \) are the time thresholds. This accessibility measure will be used to evaluate the network accessibility reliability in disasters.

**THE UPPER-BOUND LOWER-BOUND METHOD**

The collapse probability of each link \( a \) in the network can be estimated from the collapse probability of the links components:

\[
P_c = 1 - \prod_{m=ci}^{cn}(1-P_m)
\]

(5)

Where \( ci \) to \( cn \) are the components of the link in the network. In order to identify the critical link of a network, the overall accessibility reliability of the network should be estimated in all different incident scenario and combinations. In this article the upper bound lower bound method presented by Chiou and Li, as noted by Sumalee and Watling (2003), will be used to select the \( m \) most probable states of the network.

Based on these \( m \) most probable state of the network the upper-bound and lower-bound of the network accessibility reliability could be estimated as follows:

\[
\sum_{k \in A_u} A^{(k)} P(k) \leq E \leq \left(1 - \sum_{k \in A_u} P(k)\right) + \sum_{k \in A_u} A^{(k)} P(k)
\]

(6)
Where \( \hat{\Omega}_m \) is the set of \( m \) most probable states of the network and \( P(k) \) is the probability of state \( k \). This article suggests that the mean value of the upper and lower bound can be used as the expected value of the networks accessibility reliability.

In order to estimate the critical link in the network the network accessibility reliability should be estimated in two different conditions, the first condition is when the link will always stay intact, that is when the link has only one state and that is the intact state, and second is when the only state of the link is its failure, the difference in the reliability of the network in these two situations is the importance of the link in the networks accessibility reliability. The measure of importance could be computed as follows:

\[
I_l^{(i)} = E_{1i}^{(i)} - E_{2i}^{(i)}
\]

**EXAMPLE**

The network shown in Fig. 1 has been used to explain the effect of highway improvements on accessibility reliability. Let’s assume that link A has been proposed for construction. The free flow travel times and base flows on the network are shown in Fig. 1. It will be assumed that the network will be subjected to an earthquake and the damages are as follows; node 1, 200 units (e.g. injuries) nodes 2 and 4, 700 units node 5, 800 units and node 3, 2000 units. The rescue potential of each node is as in Table 1. The capacities of the links A, G and F are 2000 veh/h, the capacity of links B, C and D are 1000 veh/h and the capacity of link E is 800 veh/h. It is assumed that the probability of the scenario earthquake is 0.02. The failure probability of links A, C and D in the supposed earthquake is 0.1 and for links B and D is 0.3. The time values are assumed as in Table 2. It is supposed that BPR equation could be used for the estimation of the travel time and the trip assignment is based on the capacity restriction.

![Figure 1. Example Network](image-url)
Table 1. Rescue Potential of Nodes

<table>
<thead>
<tr>
<th>S</th>
<th>D</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>800</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>300</td>
<td>900</td>
<td>300</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>300</td>
<td>900</td>
<td>300</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Time Value

<table>
<thead>
<tr>
<th>Time after an earthquake</th>
<th>Time value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 14 h</td>
<td>1</td>
</tr>
<tr>
<td>Till 24 h</td>
<td>0.75</td>
</tr>
<tr>
<td>Till 48 h</td>
<td>0.5</td>
</tr>
<tr>
<td>More than 48 h</td>
<td>0</td>
</tr>
</tbody>
</table>

It could be seen that by using the method mentioned above the importance of each link in the overall network accessibility reliability is as in Fig. 2, this figure indicates that link A is the most important link in the network.

CONCLUSION

It had been shown that the accessibility of a network is one of the most important performance measures that could be used to evaluate the functionality of a network after a disaster occurs. Based on the reliability of the network’s accessibility and the role that each link plays in the reliability of the network the importance of a link could be estimated.

REFERENCES


Kalantari, N., 2006. Determining road transportation’s risk index based on accessibility, MS Thesis, Iran University of Science and Technology.


