Road Network Evaluation from a Reliability Perspective: An Accessibility and Network Closure Vulnerability Approach

Ramesh POKHAREL a*, Hitoshi IEDA b

a Tribhuvan University, Institute of Engineering, Kathmandu, Nepal
b Department of Civil Engineering, University of Tokyo, Japan; Graduate Institute for Policy Studies, Japan
a E-mail: ramespok@ioe.edu.np
b E-mail: ieda@civil.t.u-tokyo.ac.jp

Abstract: The reliability of transportation networks, an emerging field of research, attracts numerous researchers around the world. This paper presents a literature taxonomy of research on the reliability of road networks and an assessment of existing road network evaluation methodologies from the viewpoint of practicability, and suggests a new road network evaluation methodology for the prioritization of links to be improved in response to network closure vulnerability. The literature taxonomy includes a subdivision of reliability studies based on a broad range of relevant criteria including conceptual studies, mathematical theory, network evaluation methodologies, descriptive studies, application or case studies and ways to improve reliability. A detailed assessment of existing network evaluation methodologies is presented along with their strengths and weaknesses from a practical perspective. A network performance index is proposed for the evaluation of links. An application of the proposed methodology to the Tohoku regional road network, where numerous links were closed after the Great East Japan Earthquake, is presented.

Keywords: Road network reliability; Vulnerability; Accessibility, Disaster, Tohoku region.

1. INTRODUCTION

Natural disasters, extreme weather events and man-made incidents are the main causes of unreliability of road networks, which significantly reduces their performance. Due to failures in connectivity, many villages, cities and towns become isolated, and there are difficulties in relation to rescue and evacuation, problems in post-disaster support, increased transportation costs and losses to the economy. The severity of the weakness in the network differs from location to location. Identification of the weakest locations and critical links in a network and prioritizing them for improvement is the aim of evaluation methodologies. However, despite the growing body of literature on the reliability of road networks, existing studies have provided little advice regarding practical application.

It is not possible to upgrade all road networks at the same time, and so the question has been raised about the selection of a particular road network for an improvement project. A practical evaluation methodology that can compare the relative importance of the possible closure of various road network links is therefore necessary.

In an attempt to evaluate road network links, this paper proposes a methodology that considers the loss of accessibility of an area during emergency situations, including an evaluation of the vulnerability by redundancy concept and the introduction of threshold values.
for parameters. The proposed methodology evaluates a link’s importance in two stages. The first stage identifies and prioritizes the links in network connections, and the second stage ranks the links to increase network performance. Section 2 presents a literature taxonomy of the extant reliability research and a detailed assessment of the existing road network evaluation methodologies from a practicability perspective. A detailed formulation of the proposed evaluation methodology is presented in Section 3. An application of the methodology to the Tohoku regional road network, where numerous sections of road networks were closed immediately after the Great East Japan Earthquake, is presented in Section 4. Section 5 concludes.

2. LITERATURE REVIEW

2.1 Literature Taxonomy

This section classifies contemporary studies of the reliability of road networks using various relevant criteria. Basically, the review focuses on the study of road network disruption, impact on performance and the selection of approaches to improvement. Moreover, the literature research concentrates on searching the methodologies to identify important links in road networks that are the key to creating robust networks. There are six categories of studies that are summarized in the literature taxonomy, with due importance placed on evaluation methodologies.

2.1.1 Conceptual studies: reliability, vulnerability and other factors

Several concepts of reliability studies cover definition, conceptual classification of road network reliability, including review articles from different perspectives. Iida (1999) explains three areas of reliability research, namely, model development to investigate reliability, traffic management systems for high-level network performance and development of new evaluation procedures for planning and construction. Nicholson (2003) demonstrates that network users and planners have different viewpoints. Users are concerned about whether they can reach their destination if routes are closed, whether there will be delays and whether they will encounter unusual events. Planners focus on how many users will be unable to reach their destination, which links will be closed or congested and the expected economic cost of closure. This confirms the significance of reliability studies under emergency conditions.

2.1.1.1 Classification of reliability

A large and growing body of literature has classified reliability into travel time reliability, terminal/connectivity reliability, capacity reliability, encounter reliability and flow decrement reliability.

Travel time reliability relates to whether the destination can be reached within a specified time. Iida (1999) defines travel time (or performance) reliability as “the probability that traffic can reach a given destination within a stated time.” Similarly, Nicholson et al. (2003) define it as “the probability that a trip can successfully finish within a specified time interval (or for less than a specified cost).” Berdica (2002) defines it as “the probability that travel time between two given nodes will not exceed a given travel time.” Therefore, the higher the travel time variance, the lower the travel time reliability (Nicholson et al., 2003).
The study of terminal/connectivity reliability has a long history. Garrison (1960) studied the interstate highway system in the USA. The established definition of terminal reliability is “the probability that nodes are connected, i.e. it is possible to reach the destination” (Nicholson et al., 2003) or “a probability that there exists at least one path without disruption or heavy delay to a given destination within a given time period” (Iida, 1999). However, connectivity reliability is largely focused on congested networks (Nicholson et al., 2003). It is very important to study network connectivity after disasters so that planners can allocate resources to the weakest locations.

Capacity reliability was first introduced by Chen et al. (1999) as the “probability that the road network can accommodate a certain level of traffic demand.” Encounter reliability measures “the likelihood of users encountering a disruption on their preferred route” (Nicholson et al., 2003). They also introduce flow decrement reliability, which measures reliability using the probability of flow reduction in a degraded link. Flow will be affected in a degraded link due to the changed cost of travel between one or more OD pairs (Nicholson and Du, 1997).

2.1.2 Mathematical modeling

A large number of published studies use the mathematical theory of reliability. Various models have been used to evaluate the reliability of road networks mathematically rather than conducting practical analyses. Academically, these types of studies are very important; however, in practical terms, they are not as useful. Wakabayashi and Iida (1992) introduced a methodology for the evaluation of the terminal reliability of a road network by calculating upper and lower bounds of reliability, with a new algorithm for the Boolean absorption being developed for the calculation. Chen et al. (1999) developed a Monte Carlo simulation procedure to estimate capacity reliability. Their method calculates the maximum network capacity under the assumption that every OD pair experiences a uniform change in demand. Asakura (1999) calculated the reliability of the road network in providing information to the user by using a stochastic user equilibrium model. The expected result was supposed to be an increase in reliability, but it has been found that reliability does not always increase. Nicholson and Du (1997) proposed a mathematical model based on supply and demand, and traffic equilibrium. Their methodology estimated the reliability of the multi-model degradable (partially operating) transport network using an integrated equilibrium model. Their analysis is based on various modes not necessarily being affected by the same incident.

2.1.3 Studies recommending ways to improve reliability

The OECD (2010) suggests four policy strategies to improve the reliability of networks: 1) Physical expansion of capacity to reduce unexpected disruptions from expansion of infrastructure such as upgrading or adding rail line capacity, construction of new road links, and building new infrastructure before any incidents take place. However, the priority should be to make the network robust by improving existing infrastructure; constructing new infrastructure should only be the last-resort option. 2) Better management capacity: this includes incident management of the vulnerable parts of the network using various techniques and instruments. 3) Developing mechanisms for charging directly for reliability, most of the congestion management and cost recovery according to level of reliability. This kind of charging system should be associated with cost–benefit analysis. 4) Mitigating the cost burden associated with unreliability using information systems. With the establishment of specific
information systems, the impact and cost of incidents can be reduced; however, information itself cannot prevent incidents from occurring.

2.1.4 Descriptive studies

A large number of studies about road network disruption and its impact have been published describing practical problems and the need for policies in relation to resource allocation. Not only research papers but also case studies and official reports about road network closures are reviewed under this category. Kawasaki (2011) explains the importance of redundancy, noting the situation regarding the Japanese expressway following the Great East Japan Earthquake in 2011. Krik and Chen (2007) argue that route disruption analysis should be used as an evaluation criterion and should focus on i) defense (national strategic importance), ii) economic importance (identifying the potential impact on the economy of road closures), iii) the number of critical paths shared by a network, and iv) the availability of alternative routes. Reconstruction (2011) emphasizes the construction of disaster-resilient transport networks and the importance of incorporating redundancy. Shizuoka (2010) explains the possibility of village isolation from disaster, and Iida et al. (2000) describe the need for reliable alternative routes or redundant routes that are specifically designed for emergency situations.

2.1.5 Application studies

Several case studies have attempted to analyze real-world events as a decision tool for the efficient allocation of resources. Hou and Hsu (2005) carry out the dominant links under earthquake disaster applied on Kaohsiung City in Taiwan. Supply and demand nodes were identified based on three types of services: medical rescue, fire rescue and supply logistics. The link which has high pass frequency to connect the identified supply and demand node defined as the dominant link. Sakakibara et al. (2004) proposed a topological index to quantify road network depressiveness/concentration for the evaluation of the isolation of a district and applied it to the Hanshin region of Japan. Chang and Nojima (2001) developed a post-disaster system performance measure for the transport network in Kobe, Japan after the 1995 Hyogoken–Nambu earthquake. Their performance measure estimates the ratio of post-earthquake to pre-earthquake conditions over the total length of the network, total distance-based accessibility and areal distance. Dalziell and Nicholson (2001) calculated the risk in terms of the cost of closure of the Desert Road section of New Zealand’s major north–south road links. The total cost of road closure is assumed to be the sum of 1) the change in the vehicle operating and occupant time cost, 2) the lost user benefits from those trips cancelled or suppressed, and 3) the change in the accident cost.

2.1.6 Network evaluation methodologies

Several practical methodologies have been proposed for the identification of critical links in networks. These methodologies are easy to use and have a relevant computation time. However, as a result of several limitations, the results are not entirely plausible (see Table 1). The central aim of this research is to analyze the available evaluation methodologies from a practicability perspective and to develop a new methodology that overcomes the drawbacks of the existing methodologies.

There are six existing evaluation methodologies within the pool of reliability research that have been identified as suitable for use in practice. These methodologies are classified
into three groups based on their index calculation; the accessibility approach, the generalized travel cost approach and the disaster prevention function approach.

2.1.6.1 Accessibility approach

An accessibility index measures the socioeconomic impact of link damage after catastrophic events. The methodologies of Taylor *et al.* (2006) and Sohn (2006) both calculate the accessibility index before and after link failure and identify the most critical location in a network. However, there are numerous differences between these two methodologies.

**Hansen integral accessibility index**

Taylor *et al.* (2006) propose an evaluation index based on the accessibility of a node. This is known as the Hansen integral accessibility index, and is calculated as follows:

$$ A_i = \sum_{j=1} B_j f(c_{ij}) $$  

(1)

where $A_i$ is accessibility index for location (city) $i$, $B_j$ is attractiveness of location (city) $j$; in this study, $B_j$ has been taken as the population of location $j$, and $f(c_{ij})$ is an impedance function calculated as a reciprocal of the distance between $i$ and $j$ ($1/x_{ij}$).

The accessibility index of a node is calculated for two different scenarios under normal conditions and considering the hypothetical failure of each link, one at a time. The vulnerability is calculated as the change in accessibility after the failure of a link. A node with a high change in accessibility is defined as a vulnerable node. A critical link is one that has a higher change in accessibility in locality at the time of failure. The methodology assumes that all shortest paths (candidate links) fail in turn and accesses the consequence of failure; however, in reality, not all the shortest paths have the same probability of failure or the same level of risk in relation to a disaster. Another problem with this approach is that it fails to take into account the multiple link failure condition.

**Accessibility index under the 100-year floodplain condition**

According to Sohn (2006), the significance of a link is based on the degree of change in its accessibility index, which is calculated after a hypothetical disaster. It assumes candidate link failure under the 100-year floodplain condition, so in the floodplain the probability of link disruption is higher. However, it does not consider depth of flood and multiple link failure at the same time with same event.

Accessibility is calculated as follows:

$$ A_i = 4 \times \left[ \alpha \frac{P_i}{\sum_{j=1}^{P_i}} \sum_{j=1}^{J} \left( \frac{P_j}{\sum_{k=1}^{P_k}} \frac{d_{ij}^{-\beta}}{\sum_{k=1}^{P_k} d_{ik}^{-\beta}} \right) + (1 - \alpha) \frac{P_i}{\sum_{j=1}^{P_i}} \sum_{j=1}^{J} \left( \frac{P_j}{\sum_{k=1}^{P_k}} \frac{t_{ij}}{\sum_{k=1}^{P_k} t_{ik}} \right) \right] (i \neq j) $$  

(2)

where

- $A_i$ = accessibility score of county $i$
- $\alpha$ = weighting factor (0≤$\alpha$≤1)
- $P_{ij}$ = population of county $i$ and $j$
- $d_{ij}$ = shortest road distance between counties $i$ and $j$ under a scenario
- $d_{ij}^*$ = initial shortest road distance between counties $i$ and $j$
- $\beta$ = distance decay parameter
Average traffic between i and j on the shortest path, where AADT$_m$ is annual average daily traffic on link segment $m$, and $d_m$ is distance of link segment $m$.

The main weaknesses of this study are that it fails to address 1) the level of risk in a road link, i.e., how much deep or fringe of the flood affect the road network, 2) the parameter traffic flow, which is highly uncertain after a disaster, and 3) multiple link disruptions at the same time because it assumes only one link failure at a time.

### 2.1.6.2 Generalized travel cost approach

These methodologies consider the important factor of travel time as a transport cost for the calculation, which is in some ways similar to accessibility; however, the calculation processes are different.

### Important links and exposed municipalities

Jenelius et al. (2006) introduce the concept of important links and exposed municipalities. The main decision factor is based on the change in total travel cost between the link failure condition and the normal condition. This is calculated as follows:

$$\text{Importance}_{net}(k) = \frac{\sum_i \sum_{j \neq k} w_{ij}(c_{ij}^k - c_{ij}^0)}{\sum_i \sum_{j \notin E} w_{ij}}$$

where

- $k$ = the link that is assumed to have failed
- $w_{ij}$ = weight of OD pair, which reflects its significance in relation to the other pairs, because the calculation $w_{ij}$ is taken as traffic demand between node i-j.
- $c_{ij}^k$ = generalized travel cost between node i-j when link k has failed
- $c_{ij}^0$ = generalized travel cost between node i-j under normal conditions
- $E^{nc}$ = intact link.

When $k$ is severed, $\text{Importance}_{net}(k) = \infty$.

Although the very important parameter generalized travel cost has been considered, the methodology has some practical limitations: 1) The calculation is based on the removal of one link without considering any adverse effects. This is acknowledged by the authors, who state that “there might be a need for more realistic modeling of the failure caused by the adverse event than just removing one link at a time” (Jenelius et al., 2006). 2) It fails to address multiple link failure at the same time. 3) The parameter traffic volume is uncertain after a disaster, and therefore accurate results are unable to be calculated.

### Network Robustness Index (NRI)

Scott et al. (2006) propose a methodology called the network robustness index (NRI) to identify the critical links in a road network. This methodology calculates the total change in travel costs after removing a link, where the higher the value, the higher the criticality. The index is calculated as follows:

$$q_a = c_a - c$$
where

\[ q_a = \text{NRI of link } a \text{ in minute} \]
\[ c_a = \text{total travel time cost after removing link } a \]
\[ c = \text{total travel time cost of network under normal conditions} \]
\[ c_a = \sum t_a x_a \delta_a \]
\[ c = \sum t_a x_a \]
\[ t_a = \text{travel time of link } a \]
\[ x_a = \text{volume of traffic in link } a \]
\[ \delta_a = \begin{cases} 1 & \text{if link } a \text{ is not the link removed} \\ 0 & \text{otherwise} \end{cases} \]

This methodology gives the index value of the link, which can easily be compared with those of other links. However, the methodology fails to address the following practical realities: 1) Not every link has the same probability of damage, but it is assumed that links fail in turn. 2) There is the possibility of multiple link failure, but the model only calculates the value of link reliability one at a time. 3) The parameter traffic volume is uncertain after a disaster, and therefore accurate results are unable to be calculated.

**Degree of weakness**

Recently, MLIT (2011b) published a manual for the evaluation of road networks under emergency conditions. This calculates an index called the degree of weakness of a link. The model calculates the total travel time in a network before and after a disaster and the index is calculated as the ratio of total travel time under post-disaster conditions to total travel time under normal conditions. The index is calculated as follows.

The degree of weakness is given by:

\[ \alpha_a = \frac{T_{02}}{T_{01}} \]

where

\[ \alpha_a = \text{the degree of weakness} \]
\[ T_{01} = \sum_i \sum_j t_{ij(n)} \delta_{ij(n)} \]
\[ T_{02} = \sum_i \sum_j t_{ij(n)} \delta_{ij(n)} \]

where

\[ T_{01} = \text{total travel time under normal conditions} \]
\[ T_{02} = \text{total travel time after the disaster} \]
\[ t_{ij(n)} = \text{total travel time from municipality (i) to the nearest capital of the prefecture or expressway interchange IC j(1) and from municipality (i) to the neighboring municipality j(2)} \]
\[ \delta_{ij(n)} = 1 \text{ where the route from municipality } i \text{ to the nearest capital of the prefecture or expressway interchange IC j(1) and to the neighboring municipality j(2) passes the evaluated link (k)} \]
\[ \delta_{ij(n)} = 0 \text{ where the route does not pass the evaluated link (k)}. \]
Although the methodology does not provide any numerical probability value, it identifies the points where traffic cannot pass during a disaster. The points that are assumed to be impassable are: 1) Points where there is a possibility that an earthquake will cause damage; a) The road section lies on the tsunami inundation zone, b) A section of road where there is a possibility of landslides, rock slides or avalanches. c) A bridge constructed before 1980. 2) Points where smooth traffic flow is difficult (road width less than 5.5 m). The methodology only considers the link travel time, which is very uncertain after a disaster, but there are other important parameters such as length of the link and population in the area that remain to be considered.

2.1.6.3 Disaster prevention function approach

A recently published manual (MLIT 2011a) provides a methodology for the evaluation of redundancy using a detour ratio, which makes it very easy to evaluate the redundancy of a road link. The detour ratio is calculated as follows:

\[
\text{Detour Ratio} = \text{Min}(At_i, Al_i) \\
At_i = \frac{T_{2i}}{T_{1i}} \\
Al_i = \frac{L_{2i}}{L_{1i}}
\]

where

\[
At_i = \text{detour ratio of time} \\
Al_i = \text{detour ratio of length} \\
T_{2i} = \text{the necessary travel time for a possible alternative route (the shortest time route)} \\
T_{1i} = \text{the necessary travel time for a major route (the shortest time route)} \\
L_{2i} = \text{the distance of a possible alternative route (the shortest distance route)} \\
L_{1i} = \text{the distance of a major route (the shortest distance route)}.
\]

Four levels of a disaster prevention function have been proposed. Level A is highly protected, where the detour ratio is less than 1.5, has a low disaster risk (i.e. the links are not located at the impassable points) and is a faster route. Level B is categorized as the point that has the widest possible range of rescue and emergency supply options. Level C is categorized as the links that lie in the impassable zone, but for which the detour ratio is less than 1.5. The lowest category of link is D, which has highest risk of disaster, including a detour ratio greater than 1.5. These categories cannot provide the comparative result of links.

Table 1 presents a summary of the analysis of the existing evaluation methodologies from the practicability perspective. Various dimensions such as the socioeconomic impact of network disruption, connectivity, simplicity of data and computation process are the positive elements. These existing methodologies have some serious weaknesses, rendering them impractical. The main weaknesses of the existing evaluation methodologies are that they do not consider 1) the multiple link failure condition, 2) the criteria for the selection of links to be evaluated (although (MLIT 2011b) is somewhat practical), 3) the redundancy criteria, and 4) certain parameters; the methodologies that consider parameters like travel time and traffic flow are uncertain in emergency situations, therefore existing evaluation methodologies are considered impractical.
Table 1. Summary of analysis of existing network evaluation methodologies from a practicability perspective.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Examples</th>
<th>Methodology use</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
</table>
| Accessibility approach           | Taylor et al. (2006)      | • Accessibility index of a node is calculated under normal conditions and in the shortest path failure assumption scenario.  
• Compares differences in accessibility; the higher the change in the accessibility index, the higher the priority. | • Evaluation of socioeconomic impact of link disruption  
• Complete loss on accessibility index caused area isolation  
• Evaluation of node vulnerability and link criticality  
• Data computation process is simple and time required is reasonable | • Does not consider how much of the population is affected  
• The index is calculated based on one link failure at a time, and cannot explain the multiple link failure condition  
• The result is not plausible because it assumes that links fail one at a time |
|                                 | Sohn (2006)               | Compares the change in the accessibility index before and after the assumption of hypothetical disaster and assuming the shortest path failure at a given time lies on the 100-year floodplain. The higher the change in accessibility, the higher the priority. |                                                                                                                 | • Does not address multiple link failure condition and level of threat based on the depth and velocity of flood  
• Complex data needed, which requires a GIS database  
• Complex calculation process that requires GIS experts |
| Generalized travel cost approach | Jenelius et al. (2006)    | The link importance is computed under the assumptions of one link failure at a time and total change in generalized travel cost in a network. The link having the highest change in generalized travel cost is prioritized first. | • Numerical value of link importance is used to rank the link.  
• Data computation process is simple and time required is reasonable | • No criteria for the selection of links to be evaluated  
• Cannot solve the multiple link failure situation  
• Travel time and traffic flow are uncertain in an emergency situation |
|                                 | Scott et al. (2006)       | The network robustness index (NRI) is determined by calculating the total change in travel cost after removing a link in a network. The higher the value, the higher the criticality. | • Travel time and traffic flow are calculated based on user equilibrium assign model after assumption of each link failure | • Does not address the multiple link failure condition  
• Computation process is difficult  
• Travel time and traffic flow are uncertain in an emergency situation |
|                                 | MLIT (2011b)              | The degree of weakness is determined by calculating the ratio of increased travel time after failure of a link to the travel time under normal conditions over an entire road network. The higher the ratio, the higher the priority. | • This is a practical method for the selection of the link to be evaluated  
• Data computation process is simple and time required is reasonable | • Cannot be used in multiple link failure situation  
• The parameter travel time is very uncertain in an emergency situation  
• Does not consider the affected population |
| Disaster prevention function approach | MLIT (2011a)             | Four levels of the disaster prevention function are categorized for each link, e.g., level A is highly protected and level D has the highest risk of disaster.  
A detour ratio is introduced for the evaluation of redundancy. | • Practical method for the evaluation of redundancy  
• Categorizes the level of disaster prevention function | Individual links cannot be compared with each other so links cannot be prioritized |
3. A NEW EVALUATION METHODOLOGY

So far, this paper has focused on a brief analysis of studies on the reliability of road networks using the criterion of practicality to identify important areas for improvement. As discussed in Section 2.1.6, we propose a new network evaluation methodology to fill the gaps in the existing methodologies.

During emergency situations or when a disaster happens, three types of problems are observed. First, there is connectivity failure between two locations; there is no other option/route/link to connect the two locations, hence some areas become isolated. Second, travel time is increased due to the detour that is required. Third, traffic flow increases along the available route immediately after the disaster, causing congestion. This can have a severe impact on the community in terms of problems with rescue and evacuation, problems with post-disaster supply logistics and a negative impact on the economy.

3.1 Framework for the Practical Evaluation Methodology

In the previous section, we reviewed reliability studies and existing evaluation methodologies, and found that the existing evaluation methodologies do not solve the real-world problems. Ideally, a methodology should meet the following requirements.

- It should be based on readily available data.
- A simple calculation process and reasonable computation time is preferable, i.e., the methodology is preferable if it can be handled by each level of government authorities who are responsible for different parts of the hierarchical structure of road networks.
- Redundancy evaluation (the availability of alternative routes) should be done.
- It should be able to deal with the condition of multiple simultaneous link closures.
- It should focus primarily on network connectivity, i.e., links that are necessary to connect the isolated node should be prioritized.
- It should not be biased towards less populated areas and similar mobility range.

3.2 The Model

3.2.1 Accessibility index of an area

The Hansen accessibility index (Hansen, 1959) provides a model for the accessibility of an area with respect to the service center:

\[ i_{j}A_{j} = \frac{S_{j}T^\alpha}{T} \]

where, \( i_{j}A_{j} \) is accessibility measure of city/town \( i_{j} \) with respect to service center \( j_{i} \), \( S_{j} \) is attraction value (range of activities, number of jobs, people, etc.) of service center \( j_{i} \), \( T \) is travel time or distance between \( i_{j} \) and \( j_{i} \), and \( \alpha \) is the effect of travel time between the nodes.

The population of a service center can be used as a simple measure of attraction value because a densely populated city has a higher attraction value as a result of a wider range of opportunities.

If there is more than one hierarchy of service centers available, the index becomes:

\[ A_{i} = \frac{P_{j_{1}}}{T^{\alpha}_{i-j_{1}}} + \frac{P_{j_{2}}}{T^{\alpha}_{i-j_{2}}} + \ldots \]

where \( A_{i} \) is accessibility index of the origin node with respect to all service centers.
In general:

\[ A_i = \sum_{j=1}^{P} P_j / T_i \alpha \] (15)

Because travel time is uncertain in an emergency situation, we consider the distance between the origin node and the service center. We also take the value of \( \alpha \) as 1. Finally, the accessibility index of an area is taken as:

\[ A_j = \sum_{j=1}^{P} P_j / L_{ij} \] (16)

\( L_{ij} \) is the shortest path between origin node \( i \) and service center \( j \). The shortest path is computed using the Dijkstra algorithm, which is the most efficient and well-known algorithm for computing the shortest path in a network.

### 3.2.2 Accessibility index of a populated area

Although Hansen’s (1959) accessibility index provides the index of an area, it does not consider how many people are living in a particular area. Therefore, we improve the Hansen accessibility index by considering the population of the origin node. The final model is:

\[ A_i = P_i \sum_{j=1}^{P} P_j / L_{ij} \] (17)

The normalized model for the accessibility index of a populated area is given by:

\[ A_i = \frac{P_i \sum_{j=1}^{P} P_j / L_{ij}}{P} \] (18)

where \( P \) is the total population of the analysis area such that:

\[ P = \sum P_i + \sum P_j \] (19)

### 3.2.3 Network redundancy: evaluation of vulnerability

There are various aspects of road network vulnerability, and numerous studies have focused on vulnerability analysis. Here, we define vulnerability as the unavailability of an alternative path, i.e., network closure vulnerability. Road network links are highly vulnerable if there are no alternative routes, or if the alternative route involves a detour that drivers do not want to use, therefore they cancel or postpone the journey.

The concept of redundancy involves spare capacity such that if there is any closure on the existing path, the alternative path will continue to function. It is necessary to check the availability of alternative paths and the acceptable limit of any detours (in terms of length).

We use the detour ratio for the redundancy evaluation of available alternatives when there is a closure of one or more links on the shortest path. This very simple and practical measure for the redundancy evaluation is taken from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) manual (MLIT, 2011a):

\[ DR_{ij} = \frac{L_{ija}}{L_{ij}} \] (20)

where, \( L_{ij} \) is shortest path between \( i \) and \( j \), and \( L_{ija} \) is alternative shortest path when one or more links on the shortest path fail. In every step, the shortest path is computed using Dijkstra’s algorithm.
3.2.4 Identifying the threshold value of the critical population and distance parameters

In a simple application of the proposed model (equation 18), a less populated area can be neglected and the nearest area can be overemphasized. To minimize this effect, we introduce the parameters of critical population and distance. The sensitivity analysis method was used for the scientific identification of critical population and distance.

A set of critical populations and distances from the service center is prepared with relevant intervals. The accessibility indexes of all origin nodes are calculated for each critical population \( A_{i \text{, CRP}} \) and distance \( A_{i \text{, CRD}} \) separately. The population of the origin node is treated as a critical population if the actual population is less than the critical value. Similarly, the origin node is treated equidistance below the critical distance. Finally, the network performance index (NPI) is calculated for each CRP and CRD. A graph is plotted for population and distance separately with respect to the NPI. The benchmark measures for critical population and distance are taken where the trend line of the NPI changes dramatically. The application of this methodology is presented in the next section.

3.2.5 Network Performance Index (NPI): measurement of reliability

The reliability of the road network is defined as the connectivity performance of the overall network. Numerically, the NPI is a measurement of the reliability, i.e. the higher the NPI, the more reliable the road network. If the value of the NPI is 100%, the road network is most reliable. Pokharel and Ieda (2013) proposed this index, which is based on the restoration of a single link at a time, for the evaluation of dry-weather road networks in Nepal. In this study, the methodology is extended to evaluate network performance at any time with the restoration of multiple links. The application involving simultaneous restoration of multiple links at any point in time is presented in Section 4.1.5.

3.2.6 Use of the NPI for the prioritization of road network links

In a disaster-prone area, not all links are equally vulnerable, and it is necessary to identify the probability of link damage. Although we do not suggest any numerical analysis for the probability of the occurrence of damage, we have used the criteria from the manual published by the Japanese government (MLIT, 2011b) to select the links to be evaluated. A detailed description of the selection criteria is presented in Section 2.2.2.3. However, the criteria might differ between various countries and regions. Therefore, a two-stage process is used to prioritize the selection of impassable links for restoration. Two sets of links exist after a disaster; those that are closed (impassable) and those that are open (passable). For the purposes of our analysis, all impassable links are considered to be temporarily open links, one at a time. The step-by-step process outlined below describes the preparation of the priority list.

Stage 1: Improving the isolation state of origin nodes by providing minimum connectivity

1. Accessibility indices of all origin nodes are calculated under the worst condition. A list of isolated nodes with an accessibility index score of zero is prepared.
2. The shortest available path, \( L_{ij}, \) from isolated origin node \( i \) to service center \( j \) for each link’s restored case is identified using Dijkstra’s algorithm. The accessibility index and NPI are computed for each link return case, as shown in the flow chart (Figure 1.a).
3. The link \( k \), which has the maximum NPI, is selected as the top priority. This link is then deducted from the set of closed links and treated as a passable (open) link for the next iteration.
4. This process is repeated until all nodes are connected. However, after preparing the priority list of links for network connection, there may still be some closed links. The remaining closed links are then prioritized to increase network performance.

Stage 2: In this stage, the accessibility indices of all origin nodes are computed and added to calculate the NPI, which is the percentage improvement in the network performance due to the hypothetical restoration of a closed link k (Figure 1.b).

4. APPLICATION OF PROPOSED EVALUATION METHODOLOGY

4.1 Road Network Closure Following the Great East Japan Earthquake: Tohoku Case Study

On March 11, 2011, the Great East Japan Earthquake of magnitude 9 on the Japan Meteorological Association scale created a severe impact on the lives and property of people in the Tohoku region in Japan. A massive tsunami was generated, with waves reaching a height of almost 40 m, which claimed more than 15,000 lives. More than 4,000 people were listed as missing and more than 5,900 people were injured. There was also extensive loss of property. More than 115,000 buildings collapsed entirely and more than 160,000 buildings partially collapsed. The failure of the road network affected a wide area. Fifteen expressway routes and 69 sections on the national highway and expressway were closed after the disaster, as well as numerous sections of prefectoral and municipal roads (Kawasaki, 2011). We have applied our proposed methodology to the Tohoku regional road network.

4.1.1 Identification of critical distance and critical population

As discussed in Section 3, we performed sensitivity analysis to identify the critical population and critical distance from the service center. Different values within fixed intervals are
assumed for critical populations and distances. The methodology takes the critical value if the real figure is less than the critical value, otherwise it takes the original value.

### 4.1.2 Critical population

The NPI is calculated for different values of critical population at zero critical distance. If the city population is less than the critical population, the critical population is used, and if the city population is higher than the critical population, the city population is used. A graph is plotted with CRP on the x-axis and NPI on the y-axis (Figure 2.a). From the trend of the curve, we can estimate the critical population as 40,000, i.e., the point where the curve changes dramatically. We have also plotted the curves of different populations vs. NPI for different critical distances (Figure 2.b). The curves are almost parallel, thus we can confirm that the selected critical population value of 40,000 is correct.

Similar to the critical population, the critical distance from the service center is also identified. Figure 3.a shows the NPI at different distances when the critical population is zero. Curves showing critical distance vs. NPI for different populations are shown in Figure 3.b. The curves are almost parallel, thus we decided to set the critical distance as 15 km, where the trend of the curve changes dramatically.

### 4.1.3 Identification of isolated nodes and important links for connectivity

As explained in Section 3, we apply the proposed model to the Tohoku regional road network. At first, the process identifies the isolated nodes and prioritizes the links that are important to connect the isolated nodes. In the case of the Tohoku regional road network, we have taken the acceptable value of the detour ratio from the manual published by the Japanese government (MLIT, 2011a). A detailed explanation is presented in Section 2.2.3. The manual suggests that if the detour ratio is less than 1.5, the area is highly protected. This means that if the length of the alternative route is more than 1.5 times larger than the original shortest path, the alternative route will not be useful in a disaster situation.

The link that is identified in the first iteration is treated as a recovered link in the next iteration. In the Tohoku region, Miyako, Hanamaki, Tagajo and Minamisoma were isolated from the national highway and expressway network. Thus, the Tagajo–Sendai, Minamisoma–Soma, Miyako–Morioka and Kamaishi–Hanamaki links were selected as the first, second, third and fourth priorities, respectively (Figure 5). Although the accuracy of the methodology is difficult to verify using a case study, the result we obtained matches the Japanese government’s decision to reconstruct the expressway from Miyako to Morioka and from Kamaishi to Hanamaki (MLIT, 2011c).

### 4.1.4 Identification and prioritization of links to increase network performance after achieving network connection

After achieving network connection, 44 of the 48 closed links remained closed. As proposed in the methodology and calculation process outlined in Section 3, NPI values are calculated for each link by assuming that links are recovered one at a time. The link that provides the highest percentage improvement in network performance is selected as the top priority. The process is repeated until all remaining links are recovered. Figure 6 shows the final priority list for the closed road network links in the Tohoku region, including links that are important for network connection, and are thus given top priority and links that are important for improving network performance, and are thus given second priority.
4.1.5 Network performance during reconstruction

We use the model to identify the percentage increase in the NPI during reconstruction time. The NPI can be calculated at any time by upgrading the set of closed links. Figure 4 shows the NPI at different times during the reconstruction period. In the Tohoku region, network performance was reduced to 78% immediately after the disaster, although this had been restored to almost 99% within one month of the disaster. In this way, this methodology can be used to assess network performance at any time during the reconstruction or upgrading phase.

Similar disasters could occur in the future, creating accessibility problems after road network links are closed. Therefore, we can take the information from other discipline, simulation result or study for the assumption of links could be closed in such disaster. After obtaining reliable information, we can prioritize the road network links that need to be improved to lessen the impact of future disasters.
Figure 5. Road network links with priority number and their comparison with Japanese government decision.
Figure 6. Prioritized road network links

Regional road network links = 149
Closure link = 48
Number isolated city= 4

Links with priority number on immediately
Analysis based after disaster

Prefectural capital
Main cities
Opened Links
Closed Links
Priority No of Links for connection
Priority No of Links To increase network performance

Data Source: Road Bureau MLIT, Japan and Statistical year book 2012 Japan
5. DISCUSSION AND CONCLUSION

This paper proposed a network evaluation methodology to prioritize road network links for improvement to avoid network closure and to identify network performance at any time during restoration of damaged links. A literature taxonomy of road network reliability research, involving an assessment of existing road network evaluation methodologies from a practical viewpoint was conducted prior to developing a new network evaluation methodology. The method was applied to the Tohoku regional road network, where numerous road network links were closed immediately after the Great East Japan Earthquake, and the results were presented.

The literature taxonomy comprises six relevant criteria; conceptual studies provide a definition and classify the reliability of road networks; mathematical theory evaluates reliability in various mathematical ways; existing evaluation methodologies evaluate performance under uncertain and emergency situations; descriptive-type studies explain the real-world problems faced by the practitioner; application studies explains the results in specific areas; and studies of ways to improve network reliability demonstrate the policy issues that need to be considered.

We conducted a detailed assessment of existing road network evaluation methodologies, including strengths and weaknesses, from the viewpoint of practical application. Existing methodologies considered various dimensions such as the socioeconomic impact of network disruption, connectivity and ease of data collection and computation processes using important theoretical and practical concepts. However, the main weaknesses of existing evaluation methodologies are as follows: 1) Lack of consideration of the multiple link failure condition. 2) Lack of criteria for the selection of links to be evaluated. 3) Lack of consideration of redundancy. 4) Lack of certain parameters such as travel time and traffic flow, which are uncertain in emergency situations.

An NPI is derived to quantify the potential impact of network closure. The NPI is obtained after assumption of improving the closed links based on accessibility and network closure vulnerability approach. The cumulative effect of link improvement is observed by comparing the links. The proposed methodology prioritizes the closed road network links in two stages. In the first stage, it prioritizes the links necessary for network connection. In the second stage, it prioritizes links to increase network performance. Sensitivity analysis is also employed to identify the critical population and critical distance. These are taken as a threshold value which treated the less populated area and area within the some mobility range equally. Redundancy evaluation of alternative links is used to determine whether the proposed detour is within the acceptable range. Finally, network performance is calculated at various times during the restoration process. Interestingly, the results matched the Japanese government’s decision to reconstruct the expressway from Miyako to Morioka and from Kamaishi to Hanamaki.

This network evaluation methodology would be beneficial for disaster-prone regions where several links in the road network could be closed and numerous cities, villages and towns could be isolated. The proposed methodology can be applied to different scales of networks (i.e., at the prefecture level or the city level). By considering the probability of damage, the degree of weakness in the face of disaster from a geotechnical viewpoint and the strength of structures, this methodology could be used to guide construction techniques in the future.
REFERENCES


