Evaluation of Road Network from Reliability Perspective: An Accessibility Importance and Network Closure Vulnerability Approach.

（信頼性に着目した道路ネットワークの評価手法の開発
－道路の閉塞脆弱性を加味したアクセシビリティ重要度指標－）

By

Ramesh Pokharel

(37-106942)

A Thesis Submitted in Partial Fulfilment of the Requirement for the Degree of Master in Engineering

Signature	Date	Seal
Advisor: **Professor Hitoshi IEDA**		
Co-Advisor: **Professor Takashi OGUCHI**		

Transportation Research and Infrastructure Planning Laboratory
Department of Civil Engineering

The University of Tokyo

August 2012

Abstract:

The field of reliability research basically focuses on the performance evaluation of system. Natural disaster, extreme weather events, or manmade incidents are the causes of the unreliability of road network which significantly reduce the performance of the road network. Disconnection is the most severe problem after natural disaster. Due to failure on connection; many villages, cities or towns become isolated; difficulties in rescue and evacuation, problem on post disaster support; raises the transportation cost and loss on economy. The severity and weakness in the network are differing from location to location. Identification of weakest location and critical links in a network and prioritizing them for the improvement projects is the aim of the evaluation methodology. Despite the growing body of literature on the reliability of road network, existing studies have provided little evidence on practical application.

This thesis presents the review of reliability and vulnerability of road network studies, proposes road network evaluation methodology and presents the application results of the evaluation methodology.

The context of review is based on practicability which consist two parts. First part covers the literature taxonomy under the broad range of relevant criteria which includes conceptual studies, mathematical theory, evaluation methodology, descriptive studies, application or case studies, and the ways to improve reliability. Second part presents a detailed assessment of existing methodology of evaluation under the multidimensional perspective of practicability such as evaluation index, socioeconomic impact, area isolation, theoretical and practical importance, data requirement, calculation time and process, area wise impact of single link failure and probability of disaster. Although various dimensions were considered in the literature existing evaluation methodologies fail to consider the cumulative effect of multiple link closure condition.

Proposed evaluation methodology compares the road network links based on their performance in the network in two stages. The first stage identifies and prioritizes the important links for the network connection and second stage identifies and prioritizes the important links to increase the network performance. The methodology evaluates the socioeconomic impact of upgrading the possible closed links as an accessibility index of the village, city or town with respect to major service centre (large city). Methodology

considers the cumulative effect of multiple link closure and network redundancy. A method of sensitivity analysis has been employed to identify the critical population and critical distance which treats the very low populated and very nearest city/village or town equally.

The methodology is applied in regional road network closure which is affected by large scale disaster in Tohoku Region, Japan and rural road network closure in rainy season in Syangja district, Nepal.

The methodology can be applied to any kinds of network closure event and any level of network i.e. the different level of road administrative authority can apply to the road network under their area of responsibility. This methodology is very useful for the identification of important link, improvement against any kinds of disaster events and the disaster preparedness activities.

To Japanese people who were victimized by the Great East Japan Earthquake and Tsunami and Nepalese people who are struggling with unreliable road network.

Contents

List of figure

List of Tables

Acknowledgement

This study could have never been completed without the invaluable support and encouragement of the following people and organization.

I wish to express my sincere gratitude to my advisor, Professor Hitoshi IEDA who has supported me to change the paradigm of thinking and my life at the University of Tokyo. He was abundantly helpful and generously shared his research vision, skill, time with me. He is extremely responsible for my academic achievements. I am very proud of being his student. I would also like to express my gratitude to my co-advisor Professor Takashi OGUCHI for providing me with valuable comments, suggestion and discussion in my research work.

I am extremely thankful to Senior Assistant Professor Kiichiro HATOYAMA for his invaluable comments, suggestions and discussion in my research progress. I am also very grateful to Assistant Professor Norihisa SHIMA and Assistant Professor Naesun PARK for their invaluable comments and discussion. Special thanks to Dr. SHIMA, who manages series of laboratory seminars where I got an opportunity to enrich my skills and got valuable comments, suggestions and discussion. I am very thankful to MS. Masako KUKITA, the secretary of TRIP lab, for helping me in administrative, academic and management matter.

I am truly indebted and thankful to Mr. Teiji GOTOU and Mr. Kazuki MATSUMOTO at Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Road Bureau, Japan, who gave me invaluable time for series of discussions, meetings and datas of the Tohoku region's road network to make my research practical. I am also thankful to Mr. Gobinda DORANGA, office of the District Development Committee (DDC), Syangja Nepal, for the road network information of Syangja District, Nepal.

I also owe a debt to Dr. Surya Raj Acharya, Senior Research Fellow, Institute for Transport Policy Studies (ITPS), Tokyo for his encouragement and inspiration in my academic life.

During my academic years at the University of Tokyo my seniors and colleagues in the TRIP laboratory shared academic insights and private times with me. I very much appreciate the academic interactions, with Mr. Lee Jun. I would also like to appreciate the series of study group meetings, discussion with my lab friends and study group members, particularly Ms. Xi, Mr. Tanaka, Mr. Onogi, Mr. Kojima, Ms. Thanh Mr. Sasaki and all of my lab mates for their discussion and insightful comments. I would like to especially appreciate Mr. Prem Prakash Khatri, at International project lab for his interaction and help in difficult time.

I would like to give special thanks to Ms. Sayuri TOKUDA, my tutor, who helped me from the beginning in Japan in difficult time and for the official process of living and administrative matter.

I am indebted to the ADB-JSP program, for the financial support, Foreign Student Office (FSO), for every procedure of scholarship and admission, Japanese Language Class (JLC) to increase my Japanese communication ability and The Department of Civil Engineering, The University of Tokyo for providing me an opportunity to study in the Master course.

Finally, my single largest debt is to my life partner: Bindu SIGDEL, for her sincere support not only in personal life but also in academic matter with discussions and comments in my research.

1. Introduction

1.1. Problem description

Road networks are very important lifeline systems at the emergency situation compared to other transportation system. In11th March, 2011 devastating earthquake and tsunami, severely damaged the road network in the Tohoku region. 15 expressway and 69 section of National highway were closed (Kawasaki 2011)simultaneously; immediately after disaster. Numerous sections of prefectural and municipal roads were closed too. Due to this devastating large scale disaster, many city /town and village were isolated; their connection to the major service centre (prefectural capital or regional centre) failed and many people had to use detour route to go to the service centre. There were severe problem on evacuation and post disaster support. Congestion in survived route and significantly increased transportation cost lead the higher loss on economy. Shizuoka prefecture in Japan predicts if similar earthquake and Tsunami happens about 370villages among 1400 villages in the mountain areas and coastal area are expected to isolate((Shizuoka 2010). This implies that the road network is very much vulnerable against the large scale disaster.

In Nepal out of 28000 Km 17000 KM road (i.e. 60%.) length of road are dry weathered (Upadhyaya 2009) i.e those roads are functional only in dry weather because of flooding in the river, poor quality of pavement and landslide in hilly area. Due to this closure in the road network, large numbers of village are isolated from the major service centre. People have to walk more than one day to go to hospital and for other services.

The major problem of the road network closure is connectivity failure. To make a network in connection it is necessary to improve the road network strength against closure events. It is not possible to improve all roads at the same time due to resource and time constraints. There is a necessity of scientific methodology to evaluate the road network link and prioritize the important link for the improvement project. The basic principle of the prioritization of links is to identify the important link which can make a road network in connection even in the emergency situation.

1.2. Research scope:

In the previous section the problem of the road network is described. This research focuses on the development of methodology for the evaluation of the road network link. Like Japan, many countries are facing such kind of disaster and facing the multiple links of road network closure situation. Also many of the developing countries like Nepal are facing the road network closure situation due to weather condition which is not like a devastating disaster but problem on the community are similar. Reliability of road network is the major field of study for this problem. Numerous studies have been done for the reliability study. In this thesis; it has been tried to contribute in a very small part but from the major practical approach of reliability study.

The interaction of road network and regional planning is not explicitly considered in this research. However, socioeconomic impact of network disruption is considered as a foundation of the network evaluation methodology.

1.3. Research Objectives and Research Questions

The objective of this research is to develop the practical evaluation methodology for the road network link, finding the critical link and finally make a priority list for the improvement project. Major objectives of the research are pointed as follows:

- To make the decision tools for the improvement of road network.
- To find out the priority list of links to be improved.

In order to develop a network evaluation methodology from the reliability perspective, we need to answer the following research questions:

Research question 1: What has been done in the field of road network reliability research?

Reliability of transportation network, an emerging field of research, attracts the numerous researchers around the world. Reliability study covers the various aspect of the systems performance quality. Before development of the new evaluation methodology we need to review the reliability studies about what has been done until now. The answer to this question is illustrated by the taxonomy of the reliability research obtained from the extensive review of reliability of road network studies. Chapter 2 addresses the answer to this question.

Research question 2: What are the existing road network evaluation methodologies? Are they solving the problem?

In section 1.1, we explained the problem of network closure, the main objective of the evaluation methodology is to compare the performance of the road network link at the emergency situation, identification of critical link and make a priority list of links for the improvement project. In chapter 3 existing evaluation methodology has been selected and analyse from the multidimensional perspective of practicability. Chapter 4 deals about existing methodology which identifies the priority list of links by computational experiments. The analysis summarise the important concept and foundation of the further research and the reason why the existing methodologies are not practical.

Research question 3: How to identify the critical links of the road network and how to prioritize them for the improvement project?

As we explained in the problem description section, numerous roads network links are closed simultaneously and many village, city and town are disconnected from the service centre which caused significant reduction in the accessibility. To answer this question a network evaluation methodology is developed based on the accessibility importance and road network closure vulnerability. A Network Performance Index (NPI) compares the link. A two stage calculation process is proposed. In the first stage, priority list of the important links for the network connection and second stage priority list of the links to increase the network performance. Chapter 5 presents the formulation of the network evaluation methodology. Chapter 6 presents the application study of the proposed evaluation methodology.

1.4. The thesis outline

The thesis begins with the review of the reliability research of road network and summarises the literature taxonomy of the reliability studies in Chapter 2.

In order to develop the road network evaluation methodology, we first need to analyse the existing evaluation methodology based on the practicability. Furthermore we need to identify their impracticality so that we can develop the new evaluation methodology by overcoming the impracticality of the existing evaluation methodology. This analysis of existing evaluation methodology is done in Chapter 3.

In chapter 4, we present how we approach to the practical evaluation methodology. We use computational experiment to check the result of existing methodology.

In Chapter 5, a new road network evaluation methodology is proposed based on the accessibility importance and road network closure vulnerability.

Chapter 6 presents the application result of the proposed road network evaluation methodology. Two different application cases are presented; first one is of developed country, Japan's case, which presents road closure after large scale disaster. Second one is from developing country, Nepal's road network closure in rainy season. Last chapter (Chapter 7) deals with the conclusion and recommendations for the future work. The outline of this thesis is summarized in figure 1.1.

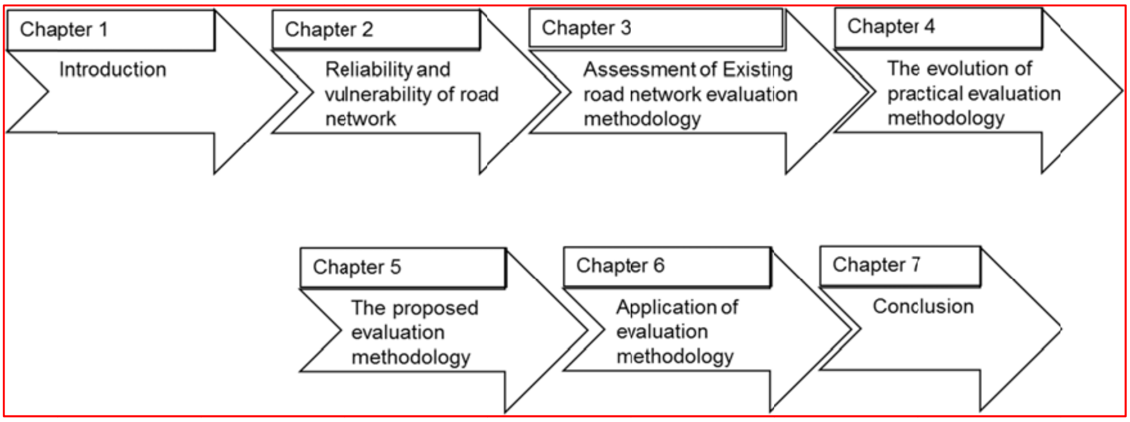


Figure 1.1: Thesis outline

2. Reliability and vulnerability of road networks

2.1. Introduction

Reliability and vulnerability of a road transportation network, a performance measure of a system or component, plays an important role for the transport network evaluation for the efficient allocation of resources. Transportation network suffers from the natural disaster and human activities, causes partial or complete disruption in the transportation system. However, the severity and weakness in the network are differing from location to location. Identification of weakest location and critical links in a network and prioritize them for the improvement projects is the aim of the evaluation methodology.

Indeed, developing a practical methodology to evaluate the road network, finding the weakest link and prioritize among them is quite difficult and complex. Numerous studies have been done to develop the methodology of evaluation; however practical methodology is still lacking.

Several authors have written review articles on reliability measures, often focusing on certain perspectives such as vulnerability, travel time reliability, connectivity reliability, capacity reliability and encounter reliability (Berdica 2002; Nicholson, Schmocker et al. 2003). Literature review made literature taxonomy of the contemporary studies of reliability of road network. Which classifies the reliability of road network studies as (a) Conceptual studies, (b) Mathematical theoretical studies , (c) Evaluation methodology, (d) Descriptive study, (e) Application study and (f) The ways to improve reliability and 2) detailed assessment of the existing practical methodology of evaluation under multi-dimensional criteria including evaluation index, data requirement, calculation time , probability of adverse events, theoretical and practical importance, one link failed and area wise impact and socioeconomic impact of road network disruption . This review is based on extensive literature study, will approach the subdivision of existing studies in section 2, detailed assessment of the existing practical evaluation methodology in section 3, and conclusion of the literature in the last section.

2.2. Review of road network reliability studies

This section reviews the existing study of the reliability of road network under different subdivided criteria. The division of the existing reliability study is based on practicality of the methodology of evaluation.

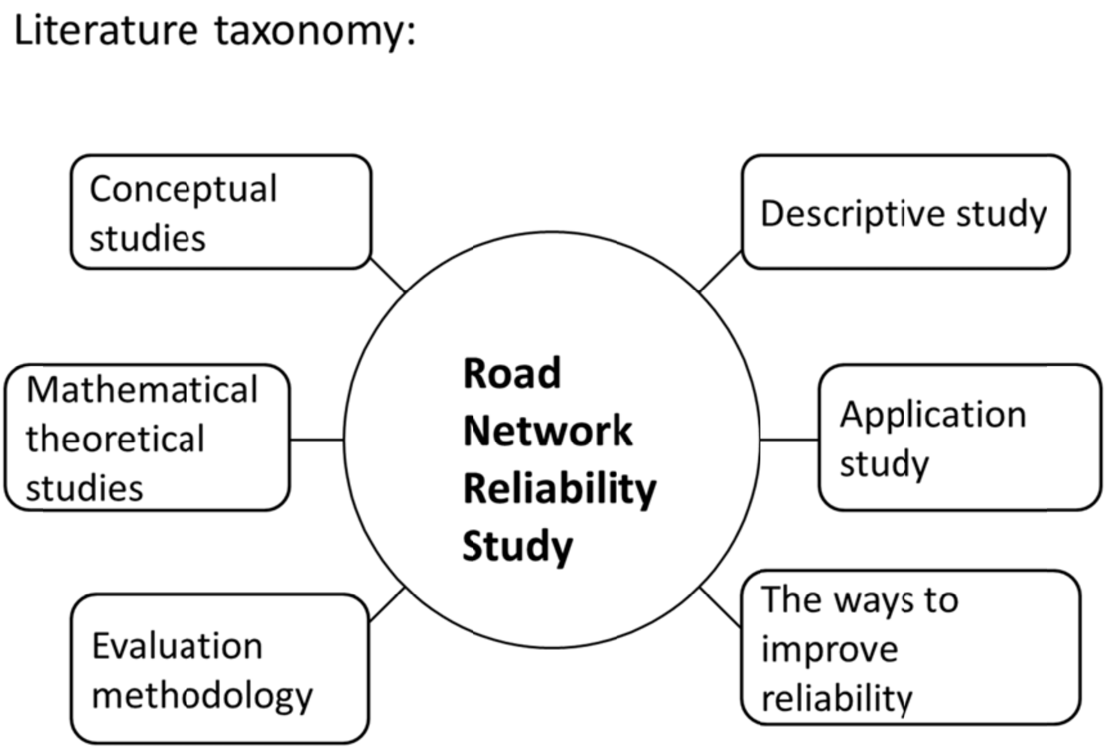


Figure 2.1: Literature taxonomy
Source: (Pokharel and Ieda 2012)

2.2.1. Conceptual studies: Reliability, Vulnerability and others

Several concept of reliability studies cover definition, conceptual classification of the road network reliability including review articles from different perspective. (Iida 1999) explains three area of reliability research, first one is "Model development which is capable to investigate the reliability of road network". Second "establishment of traffic management system is able to provide high level of network performance to the users". The last one is "development of new evaluation procedure for optimizing planning, construction and management of road network that incorporates road network reliability." (Nicholson 2003) demonstrates that network users and planners have different viewpoints. From users viewpoint, some questions may arise about reaching the destination, usual route likely to close or not, possibility of encountering the unusual event, delay on usual route or confusion about the decision due to changing the route, cancel the trip or postpone the trip, or change the destination. Similarly, from the planner's viewpoint, how many users could not reach the destination? Which links will be congested or closed (i.e. are weak links)? Which are the important links in the network? Which are critical (important and weak) links? What are the expected economic costs of closure? This implies the significance of reliability studies under emergency condition.

2.2.1.1.Definition of terms:

Reliability:

Reliability has been defined mainly from two perspectives. First one has been taken from system reliability perspective such as "Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered" (Wakabayashi and Iida 1992; Berdica 2002). Such definition does not clearly define the reliability of road network. The characteristics of road network are different from the system engineering concept (Iida 1999). Second, from service quality perspective such as "the ability of the transport system to provide the expected level of service quality, upon which users have organized their activities" (OECD 2010). Therefore in the transportation sector all service standard of a network is already achieved at the construction period. However the reliability studies relate to the reduction in the service qualities due to natural and human made adverse events.

Vulnerability:

The concept of vulnerability as defined by the Berdica (2002) " a susceptibility to incidents that can result in considerable reduction in road network serviceability." (Taylor, Sekhar et al. 2006) define the vulnerability in terms of node vulnerability and link criticality. "A network node is vulnerable if loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node, as measured by a standard index of accessibility" and "a network link is critical if loss (or substantial degradation) of the link significantly diminishes the accessibility of the network or of particular nodes, as measured by a standard index of accessibility." (Husdal 2004) suggests that vulnerability and reliability can be analyzed through the cost benefit perspective; such as vulnerability is a consequential cost of an operational degradation and reliability is a consequential benefits of an operational improvement. However, quantification of every term in monetary value is quite difficult and complicated.

Risk:

Risk is defined as the probability of hazard and the consequences of the result (Berdica 2002) i.e. expectation of hazard or threat. The evaluation of risk includes level of probability of hazard i.e. lower to highest ; consequence of hazard minor to major and identify the critical links (Nicholson, Schmocker et al. 2003). (Husdal 2004) demonstrates that the risk is a product of vulnerability of the occurrence of external events and probability of threat.

Resilience:

Resilience is the capability of a system that can return to the normal system or can recover quickly from the difficult situation. In the road transportation, (Berdica 2002) defines the resilience as a capability of network to restore the serviceability or capability of reaching the new state of equilibrium .

Robustness:

"Robustness is the extent to which, under pre specified circumstances, a network is able to maintain the function for which it was originally design" (Snelder 2010). And vulnerability is the opposite of the robustness(Berdica 2002).

Redundancy:

The backup alternative i.e. existence of alternative route/link in a road network between origin and destination can result less serious consequence in case of disruption in some part of network (Berdica 2002). Robustness of network increases with the presence of redundancy (Snelder 2010). However, redundancy depends upon the nature of threat, for instance, huge rainfall or snowfall can close all the route and no redundancy presence(Berdica 2002).

2.2.1.2.Classification of reliability:

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

Travel time reliability:

A considerable amount of literature has been published on travel time reliability. These studies are focused on whether the travel time taken to reach the destination is within a specified time or not. (Iida 1999) defines "Travel time (or performance) reliability is defined as the probability that traffic can reach a given destination within a stated time". Similarly (Nicholson, Schmocker et al. 2003) give a definition as " The probability that a trip can successfully finish within a specified time interval (or less than a specified cost)". And Berdica (2002) defines "the probability that travel time between two given nodes will not exceed a given travel time." So higher the travel time variance is, the lower will be the travel time reliability (Nicholson, Schmocker et al. 2003). A stochastic model is proposed by (Yin and Ieda 2001) to investigate the day to day travel variation of travelers on travel time reliability .

Connectivity/Terminal Reliability:

Numerous studies have been attempted to explain the connectivity reliability. It has a long history; (Garrison 1960) studies the interstate highway system of USA . The established definition of the terminal reliability is " the probability that nodes are connected, i.e. it is possible to reach the destination"(Nicholson, Schmocker 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) . The major concern in the connectivity reliability is weather the links are opened or closed, with the state of link "*a*" is represented by the 0-1 variable (Wakabayashi and Iida 1992; Bell and Iida 1997; Iida 1999). The stochastic variable x_i represents the state of link *i* with the value 1, if the link is functional and 0 otherwise (Berdica 2002). However connectivity reliability is largely focused on the congested network (Nicholson, Schmocker et al. 2003) It is very important to study the network connectivity after disaster therefore planner can allocate the resources at weakest location.

Capacity, Encounter, and Flow Decrement Reliability:

Various kinds of reliability concept have been introduced by different studies. Capacity reliability is introduced first by (Chen, Yang et al. 1999) as a "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, Schmocker et al. 2003). They also introduce flow decrement reliability which measures the reliability by using the probability of reduction in flow in a degraded link. Flow will be affected in a degraded link due to affected cost of travel between one or more OD pairs (Nicholson and Du 1997).

2.2.2. Mathematical, theoretical study of reliability:

There is a large volume of published studies which used mathematical theory of reliability. Mathematical model have been used to evaluate the reliability of road network mathematically rather than practical application. Academically these types of studies have high importance, however, practically not so useful. (Wakabayashi and Iida

1992) introduce a methodology for the evaluation of terminal reliability of a road network by calculating upper and lower bounds of reliability. A new algorithm for the Boolean absorption has been developed for the calculation. (Chen, Yang et al. 1999) develop a Monte Carlo simulation procedure to estimate the capacity reliability. The method calculates the maximum network capacity with the assumption of every OD pair having uniform change of demand. (Asakura 1999) calculates the reliability of the road network with providing information to the user by using stochastic user equilibrium model. The expected result was supposed to increase the reliability but actually it does not always increase. (Nicholson and Du 1997) propose a mathematical model based on supply and demand and traffic equilibrium. The methodology carried out the reliability of the multi model degradable (partially operating) transport network by using integrated equilibrium model. The analysis is based on the different mode not necessarily affected by the same incident. A sensitivity analysis is used to identify the important component in degradable transportation system with the analysis of the socioeconomic impact of system degradation. (Bell 2000) proposes a game theory approach for the measurement of road network reliability. In the non-cooperative game, network user and evil entity are the two players. Network user seeking the path to minimize the expected trip cost and on the other side evil entity choosing the link performance scenario to maximize the expected trip cost, finally result has got an equilibrium condition, the user unable to reduce the expected trip cost by changing his path choice probabilities and evil entity also unable to increase the expected trip cost.

Numerous methodologies have been introduced mathematically for the evaluation of road network link for the resource allocation. A two stage stochastic program proposed by (Peeta, Sibel Salman et al. 2010) , in the first stage they identify the links to be invested and second stage, the minimum traversal cost between O-D pairs is determine. Strength of each link is measured based on the probability of the link component (Bridges and Viaducts) remain operational after disaster. (Sánchez-Silva, Daniels et al. 2005) propose the operational reliability of the transport network for the efficient allocation of resources, considering the state of network, is defined by the Markov model, through physically related failure and repair rate of each link, such that rate can be changed with investment . They also consider reaction of network user with the failure of links along route and waiting time for the user until the link is repaired.

2.2.3. Evaluation Methodology:

Several practical methodologies have been proposed for the identification of critical link in the network. (Taylor, Sekhar et al. 2006) suggest the condition of node vulnerability and link criticality by calculating the accessibility index of the link at the emergency situation. The accessibility index gives a socioeconomic impact to the society and finds out the link which has highest change in the accessibility index after disaster compared to normal condition. (Sohn 2006) also suggests accessibility index in a flood plain, the considered link is taken only from the 100 year floodplain. (Jenelius, Petersen et al. 2006) suggest very similar concept to the (Taylor, Sekhar et al. 2006) such as link importance and municipality exposure, each and every link is evaluated through the change in generalized travel cost. (Scott, Novak et al. 2006) suggest a network robustness index (NRI) of a link. The NRI calculates the change in total travel cost in a network due to failure of particular link. (MLIT 2011b) evaluates the degree of weakness of the specific network link which lies under vulnerable scenario and calculate the ratio of total travel time in a network before and after disaster. (MLIT 2011a) analyzes the degree of isolation by calculating the detour ratio and disaster tolerance function. A detailed assessment from multiple viewpoints is presented of these practical methodologies in section 3.

2.2.4. Descriptive study:

A large volume of studies about the road network disruption and its impact has been published describing the practical problem and requirement of policy for resources allocation. Not only research paper but also case study or some official report about the road network closure reviewed under this category. (Kawasaki 2011) explains in his presentation, importance of the redundancy and Japanese expressway served as a redundant network on the great east Japan earthquake in 2011. (Consortium 1996) explains the socioeconomic impact in the society due to disruption of transportation network, causes losses of accessibility, disrupt the economic activity across the region and nation, rescue and evacuation problem. It argues the need of pre-disaster policies and raises the issues of prioritizing the allocation of the resources to the multiple impacted areas. (Krik and Chen 2007) argue in their work route disruption analysis as an evaluation criteria and should be focused on the i) defense (national strategic importance), ii) economic importance- Identify the potential impact on the economy due to roadway closure, iii) How many critical path in a network share a given component ,iv) availability of alternative route. (Reconstruction 2011) emphasizes on the construction of disaster resilience transport network and securing the redundancy. (FHWA 2008) suggests the necessity of the durable infrastructure system, tools to identify the critical routes. (Shizuoka 2010) explains about the possibility of village isolation from disaster. (Ramirez, Peeta et al. 2005) suggest necessity of critical route which can survive under earthquake should minimize the total travel time and cover the larger population. (Iida, Kurauchi et al. 2000) describe the necessity of the alternative reliable route or redundant route which is especially designed for the emergency condition.

2.2.5. Application study:

Several case studies have been attempted to analyze the real practical world as a decision tools for the efficient allocation of the resources. (Hou and Hsu 2005) carry out the dominant links under earthquake disaster applied on Kaohsiung City in Taiwan. Supply and demand node were identified based on the three types of service; medical rescue, fire rescue and logistic supply. The link which has high pass frequency to connect the identified supply and demand node among the entire replaceable paths and probability more than 0.5, defined as the dominant link. Enumeration algorithm has been developed to find out the dominant link in a complex network. (Sakakibara, Kajitani et al. 2004) purpose a topological index to quantify road network depressiveness/concentration for the evaluation of isolation of a district and applied in Hanshin region of Japan. (Susilawati and Taylor 2008) apply an accessibility/remoteness index of Australia to evaluate the road network in a Green Triangle Region of Australia. Change in accessibility after assumption of candidate link failure has been calculated. The index is based on the distance to the service center from the remote village or municipality. (Chang and Nojima 2001) develop the post disaster system performance measure of the transport network in Kobe, Japan after 1995 Hyogoken –Nambu earthquake. The performance measure estimates the ratio of post-earthquake to pre-earthquake condition of the total length of network, total distance based accessibility and areal distance based accessibility ranges from 0 (non-functional system) to 1 (fully functional system). (Dalziell and Nicholson 2001) calculate the risk of closure of the Desert road section of New Zealand's major north-south road links in terms of cost. The total cost of road closure assumed to be sum of 1) the change in the vehicle operating and occupant time cost, 2) The lost user benefit from those trips are cancelled or suppressed and 3) Change in the accident cost .

2.2.6. The ways to improve reliability:

Recently (OECD 2010) suggests four policy strategies to improve the reliability of the network such as 1) Physical expansion of the capacity, to reduce the unexpected disruption in service expansion of infrastructure such as upgrading and adding line capacity ,construction of new road link , built new infrastructure before any incidents take place , however, priority should be to make robust network by improvement of existing infrastructure; building new should only be the last option. 2) Better management capacity- this includes incident management of the vulnerable part of the network by using different 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 system. With the establishment of the specific information system, impact and cost of the incident can reduce; however, information itself cannot prevent the incidents.

Table 2.1: Summary of Review of Reliability Study

Reliability study	Examples	Characteristics
Conceptual study	(Iida 1999) ,(Nicholson 2003), (OECD 2010),(Taylor, Sekhar et al. 2006) ,(Berdica 2002),(Nicholson, Schmocker et al. 2003),(Garrison 1960),(Bell and Iida 1997) (Chen, Yang et al. 1999),(Nicholson and Du 1997),(Husdal 2004),(Snelder 2010).	• Defining the various terms and concept of reliability. • Reviewing the contemporary study.
Mathematical theoretical study	(Wakabayashi and Iida 1992), (Chen, Yang et al. 1999), (Asakura 1999),(Nicholson and Du 1997),(Bell 2000),(Peeta, Sibel Salman et al. 2010),(Sánchez-Silva, Daniels et al. 2005)	• Mathematical solution of the problem. • Imported from the system performance evaluation of other discipline. • Difficulty to use in practical field. • Complex solution methodology, time consuming and requires highly skilled researcher. • Results are not relevant practically.
Practical methodology of evaluation	(Taylor, Sekhar et al. 2006),(Sohn 2006),(Jenelius, Petersen et al. 2006),(Taylor, Sekhar et al. 2006), (Scott, Novak et al. 2006) ,(MLIT 2011b), (Dalziell and Nicholson 2001)	• Simple evaluation methodology. • Easy to use. • Not very complex data. • Less time consuming. • Have some limitation so result is not plausible. • Could be a foundation for the new evaluation methodology.
Descriptive study	(Kawasaki 2011), (Consortium 1996),(Krik and Chen 2007), (Reconstruction 2011),(FHWA 2008),(Shizuoka 2010),(Ramirez, Peeta et al. 2005), (Iida, Kurauchi et al. 2000)	• Addresses the problem on the field • Addresses the problem faced by the practitioner • Challenge to solve the problem. • Requirement of evaluation methodology
Application study of evaluation methodology	(Hou and Hsu 2005),(Sakakibara, Kajitani et al. 2004),(Chang and Nojima 2001),(Susilawati and Taylor 2008)	• Case study of specific area. • Typical application study.
The ways to improve reliability	(OECD 2010)	• Policy recommendation for the improvement of reliability.

3. Detailed assessment of existing road network evaluation methodology

There are six existing practical methodologies selected for the analysis. These methodologies are classified into three groups based on their index calculation. Table 2 summarizes the evaluation methodology and their objectives.

Table 3.1: Summary of selected evaluation methodology

Method	Author	Objectives	Methods
Accessibility approach	(Taylor, Sekhar et al. 2006), (Sohn 2006)	• Develop the methodology to identify the critical location in a road network. • Establish the priority list for improvement of network link.	• Calculate the accessibility index of a location at normal and shortest path failure assumption scenario. • Compare the index among the entire link, higher the change in accessibility index; higher is the priority.
Generalized travel cost	(Jenelius, Petersen et al.	• To develop the methodology for	• Index is calculated with the assumption of link

approach	2006),(Scott, Novak et al. 2006),(MLIT 2011b)	the evaluation of link based on the generalized travel cost.	failure and total change in the generalized travel cost in a network. Link having higher change in generalized travel cost is prioritized first.
Disaster prevention function approach	(MLIT 2011a)	Comparing the links by disaster tolerance and redundancy.	• By calculating the detour ratio and accessing the level of links disaster protection function.

During emergency situation, or when extreme disaster happens three kinds of problem are observed. The first one is connectivity fails between two locations; there is no other option/route/link to connect between the two locations, hence, some area becomes isolated. Second, travel time is increased due to detour route. Third, traffic flow increase in the other survived route immediately after the disaster and causes the problem of capacity/congestion. A severe impact on the community can arise such as problem on rescue and evacuation, problem on post disaster logistic supply and highly impact on economy.

Road network planners need a very simple and practical decision making tools to decide where they should concentrate their resource to make robust network. However, current methodologies cannot address the needs of practitioner but leave very important message for the development of new methodology. The major question is why these methodologies cannot address the need of practitioner? What are the weaknesses of these methodologies? Which parts of these methodologies are important and can be used to develop the new methodology? We analyse here from multi-dimensional perspective.

3.1. Accessibility Approach:

Accessibility index measures the socioeconomic impact of link damage after catastrophic events. The common characteristics of methodology (Taylor, Sekhar et al. 2006) and (Sohn 2006) both calculate the accessibility index before and after assumption of link failure and identify the most critical location on a network. However, there are many differences in these two methodologies.

3.1.1. Hansen integral accessibility index and accessibility/ Remoteness Index of Australia

(Taylor, Sekhar et al. 2006) propose two index for the evaluation of road network link.

Hansen integral accessibility index:

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

Where, A_i accessibility index for a location (city) *i*

B_j is attractiveness of location (city) *j*, in this research B_j has been taken as population of location j. $f(c_{ij})$ is an impedance function calculated as a reciprocal of distance between i and j ($1/x_{ij}$)

Normalized value of accessibility Index

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

Accessibility/Remoteness Index of Australia

$$\mathrm{ARIA}_{\mathrm{iL}} = \sum_{L} \min\left\{3, \frac{x_i}{\overline{x}_L}\right\}$$

Here $\overline{x}_L$ is the mean road distance of all localities to the nearest service centre. Service centre are categorized as (A, B, C, D, E) based on the population on the city highest to lowest. The maximum value of ARIA will be 15.

Accessibility is calculated at normal condition and after assumption of failure of each link one at a time. The vulnerability is calculated by change in accessibility after failure of a link. The node with higher change in accessibility is defined as vulnerable node. Critical link is that link which has higher change in accessibility in locality at the time of failure assumption. This methodology clearly defines the node vulnerability and link criticality. Evaluating road network in terms of accessibility index is very important, clear measurement and also practical; this methodology claims socioeconomic impact of network degradation and measures the regional network vulnerability. Data collection and calculation procedure are simple. However, the study fails to consider any specific event which caused the multiple road section closure. It assumes all shortest paths (candidate links) fails in turn and accesses the consequence of failure, in reality all shortest path do not have same probability of failure or same risk from the disaster and another problem with this approach is, fails to take the multiple link failure condition into account.

3.1.2. Accessibility index under 100 year floodplain

The second methodology(Sohn 2006) of accessibility group also calculates accessibility index at normal condition and disaster condition and significance of link is based on the higher change in the accessibility index after a hypothetical disaster. One difference is it assumes candidate link failure under 100 year floodplain, 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

$$A_i = 4 \times \left[\alpha \frac{P_i}{\sum_{k=1}^{24} P_k} \sum_{j=1}^{23} \left(\frac{P_j}{\sum_{k=1}^{24} P_k} \frac{d_{ij}^{-\beta}}{\sum_{k=1}^{24} d_{ik^*}^{-\beta}} \right) + (1-\alpha) \frac{P_i}{\sum_{k=1}^{24} P_k} \sum_{j=1}^{23} \left(\frac{P_j}{\sum_{k=1}^{24} P_k} \frac{t_{ij}}{\sum_{k=1}^{24} t_{ik^*}} \right) \right] (i \neq j)$$

Where

A_i= accessibility score of county *i*

α= weighting factor (0<α<1)

$P_{i(j)}$ =Population of county *i(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

β= distance decay parameter

$$t_{ij} = \frac{\sum_{m=1}^{n} AADT_m d_m}{d_{ij}}$$ Average traffic between i and j on the shortest path

AADTm= annual average daily traffic on link segment m

d_m= distance of link segment m

First part of formula is accessibility based on distance criteria only if the value of α is 1 and including second part is distance traffic volume criteria.

Accessibility deterioration:

$$A^j = \sum_{i=1}^{24} A_i - \sum_{i=1}^{24} A_i^j = \sum_{i=1}^{24} \left(Ai - A_i^j \right)$$

Where

A_j= accessibility deterioration when link *j* is disrupted

A_i = accessibility score of County *i* before disruption of link

A_i^j =accessibility score of County *i* after disruption of link *j*

OR

If probability of flood damage of a link *j* p_j is available then accessibility deterioration is

$$A^j = p^j \sum_{i=1}^{24} \left(Ai - A_i^j \right)$$

This methodology is more practical than previous one because it considers 100 year flood plain and candidate link is selected as link lies on the 100 year floodplain or considers the probability of damage. Although, the methodology considers the floodplain and specific area but it can be used as a general methodology and can consider the other disaster with disaster hazard map or probability of damage or event occurring. The main weakness of the study are 1) fails to address the level of risk in a road link i.e. how much deep or fringe of the flood affect the road network .2) Failure to consider the change in traffic flow after disruption of a link 3) It fails to address the multiple link disruption all at a time because it assumes only one link failure at a time.

3.2. Generalized Travel Cost Approach:

The methodologies consider the important factor as a transport cost (travel time) for the calculation which is somehow similar to accessibility, however, theoretically, conceptually and calculation process are different.

3.2.1. Important Link and Exposed Municipality.

A very similar to node vulnerability and link criticality (Taylor, Sekhar et al. 2006)'s methodology, (Jenelius, Petersen et al. 2006) introduce the concept of important link and exposed municipality. The main decision factor is based on change in total travel cost between link failure condition and normal condition. A detailed calculation is as follows.

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

Where, k= Link assumed to be failure

w_{ij}= Weight of OD pair reflects its significance in relation to the other pairs, for the calculation wij is taken as traffic demand between node i-j.

c_{ij}^k = generalized travel cost between node i-j when link k is failed

c_{ij}^0 = generalized travel cost between node i-j at normal condition

E^{nc} = non cut link

When k is cut link

$\text{Importance}_{\text{net}}(\text{k}) = \infty$

Also this study introduced the concept of unsatisfied demand when link k is closed, the travel cost between nodes become infinite. The finite and infinite unsatisfied demand is defined as

$$u_{ij}^k = \begin{cases} x_{ij} \text{ if } c_{ij}^k = \infty \\ 0 \text{ if } c_{ij}^k < \infty \end{cases}$$

Where x_{ij} is travel demand from demand node i to j

Importance of link k at unsatisfied demand

$$\text{Importance}_{net}^{uns}(\text{k}) = \frac{\sum_i \sum_{j \neq i} u_{ij}^k}{\sum_i \sum_{j \neq i} x_{ij}} k \in E$$

For

$k \in E^{nc}$, $\text{Importance}_{net}^{uns}(\text{k}) = 0$

From the above equations the importance of the link is proportional to the change in generalized travel cost. Study addresses the theoretical aspect of link criticality and municipal exposure and calculation data and time are suitable for the practical application; however, this does not give the real world result. Although very important parameter generalized travel cost has been considered, the methodology has some practical limitation. 1) The calculation process is based on the removing of one link without considering any adverse event also realize by the authors “ there might be need for more realistic modeling of the failure caused by the adverse event, then just removing one link at a time”(Jenelius, Petersen et al. 2006). 2) Fails to address the multiple links failure all at a time.

3.2.2. Network Robustness Index (NRI)

(Scott, Novak et al. 2006) propose a very similar methodology called network robustness index (NRI) to identify the critical link in a road network. This methodology calculates the total change in travel cost after removing a link and higher the value higher the criticality. Index is calculated as follows

Network robustness index (NRI) of a link a is

$q_a = c_a - c$

Where,

q_a = Network robustness index (NRI) of a link a in minute

c_a = Total travel time cost after removing of link a ,

c= Total travel time cost of network at normal condition

$$c_a = \sum_a t_a x_a \delta_a$$

$$c_a = \sum_a t_a x_a$$

t_a = Travel time of link a

x_a = volume of traffic in a link a

$$\delta_a = \begin{cases} 1 \text{ if link } a \text{ is not the link removed} \\ 0 \text{ otherwise} \end{cases}$$

This model runs in the TransCAD program first to calculate the travel time and traffic flow at normal condition by using user equilibrium assign model and remove each link one at a time sequentially and then again calculate the travel time and traffic flow. The model argue that the network users who do not use the removed link may be rerouted based on the user equilibrium principle.

This methodology gives the value of index which can be compared easily with the other link and the ranking of link can be done, data are simple and calculation software is needed. However, the main weakness of the study is failure to address the practical field situation i.e. 1) every link do not have same probability of damage while it assume link failure in turn.2) there is the possibility of multiple link failure while the model calculates the value of link reliability one at a time.

3.2.3. Degree of Weakness

Recently (MLIT 2011b) publish a manual for the evaluation of road network at emergency condition calculates the index called degree of weakness of a link. The model calculates the total travel time in a network before and after disaster and index is calculated as the ratio of total travel time at disaster condition to total travel time at normal condition. This methodology does not remove all the links in a network like previous methodology. The model of this methodology is as follows:

The degree of weakness

$$\alpha_0^k = \frac{T_{02}^k}{T_{01}^k}$$

Where, α_0^k = the degree of weakness

$$T_{01}^{k} = \sum_i \sum_j t_{ij(n)} \delta_{ij(n)}$$

$$T_{02}^{k} = \sum_i \sum_j t_{ij(n)} \delta_{ij(n)}$$

T_{01}^{k} =Total travel time at normal condition

T_{02}^{k} =Total travel time after disaster event

$t_{ij(n)}$ = Total travel time from municipalities (i) to the nearest capital of the prefectures or expressway IC j (1) and the travel time from municipalities (i) to the neighboring municipalities' j (2).

$\delta_{ij(n)}$ = 1, the route from municipalities *i* to the nearest capital of prefecture or expressway IC j (1) and to the neighboring municipalities' j (2) can pass evaluated link (k).

$\delta_{ij(n)}$ = 0 do not pass the evaluated link (k)

The main important approach of this methodology is its probabilistic approach, the selection of link (k) is crucial part and identified based on the possibility of damage, however , it does not consider any numerical value of probability but it identifies the point where traffic cannot pass during disaster .The points to be assumed as a impassable are : 1) Points where the probability of following earthquake causes damage a)The road section lies on the Tsunami inundation zone, b) Section of road where possibility of landslide, rock sliding, avalanches. c) Bridge constructed before 1980. 2) Points where smooth traffic flow is difficult (road width less than 5.5m). This methodology considers the real world situation and significantly reduces the number of links to be evaluated. However, it has considered the link travel time only, there are other important parameter like traffic flow, length of the link, population in area are left to be considered. And there is lacking of level of threat from the disaster i.e. the risk on the particular link.

3.3. Disaster Prevention Function Approach:

The recently published manual (MLIT 2011a) gives an evaluation methodology for the evaluation of redundancy by using detour ratio. It is very simple and easy to evaluate the redundancy of a road link. The detour ratio is calculated as follows:

$Detour\ Ratio = Min(At_i, Al_i)$

$$At_i = \frac{T_2^i}{T_1^i}$$

$$Al_i = \frac{L_2^i}{L_1^i}$$

Where

At_i = Detour ratio of time.

Al_i = Detour ratio of length.

T_2^i =The necessary time of possible alternative route (the shortest time route).

T_1^i =The necessary travel time of major route (The shortest time route).

L_2^i =The distance of possible alternative route (The shortest distance route).

L_1^i = The distance of major route (The shortest distance route).

Similarly, in a degree of weakness, the disaster tolerance (risk of incidents) is evaluated based on the riskiness criteria, identifies the point where traffic cannot pass during disaster. The points to be assumed as an impassable are: 1) Points where the following earthquake damage a) the road section lies on the Tsunami inundation zone, b) Section of road where possibility of landslide, rock sliding, avalanches. c) Bridge constructed before 1980. 2) Points where smooth traffic flow is difficult (road width less than 5.5m). The disaster prevention function is levelled as in table below. The four level of disaster prevention function has been proposed. Level A is highly protected where the detour ratio is less than 1.5, has low danger of disaster risk (i.e. the links is not located the impassable points) and faster route. Level B is categorized as the point which has the wide range of possibility of rescue and emergency supply. Level C is categorized as the links which lie on the impassable zone but detour ratio is less than 1.5. The lowest category of link is D, which has highest risk of disaster including detour ratio greater than 1.5. Table 3 shows the evaluation criteria.

Disaster prevention function approach categories the level of route disaster prevention functions as A, B, C, and D; but does not give the comparative result of the routes because there is a possibility of more than one route lying on the same level and single link may lie on the various route. So, more than one route could be affected by the same vulnerable link and cannot give the comparative result of the links.

Table 3.2: Criteria for Disaster Prevention Function approach

Level of link disaster prevention function	Disaster tolerance (The riskiness of disaster)	Redundancy (Vulnerability)
	Low danger of disaster of major route = ○ and faster route = ◎	The detour ratio of alternative route that has low danger of disaster is less than 1.5 =○
A	◎	○
B(BB)	○(◎) {(BB) Where the place is located as transportation point of wide rescue and emergency supply }	- (No need to evaluate redundancy)
C	×	○
D	×	×

Source (MLIT 2011a)

Table 4, below summarizes the data requirement for each practical evaluation methodology. Table 5, below summarizes the consideration of multiple dimension of practicability approach of existing evaluation methodology. Table 6, below summarizes the analysis of the existing methodologies based on the multidimensional viewpoint of practicability with positive and lacking perspective. Some of the methodologies have not considered the probability of disaster event. They only assume the failure of a link at a time and calculate the change in indices, so that they do not represent real practical world. Some of the methodologies considered the probability of disaster event without considering the any numerical value of probability. They only select the links to be evaluated from the disaster possible area. Therefore comparing among the links is difficult due to lack of any measurable value.

Table 3.3: Data requirement for the calculation process for existing methodology

Approach	Studies	Data Requirement						
		Travel time/ Cost	Link length	Traffic flow/ Demand	Population in location	Hazard map	Level of riskiness	Probability of event
Accessibility	(Taylor, Sekhar et al. 2006)	+	+	-	+	-	-	-
	(Sohn 2006)	-	+	+	+	+	-	+
Generalized Travel cost	(Jenelius, Petersen et al. 2006)	+	-	+	-	-	-	-
	(Scott, Novak et al. 2006)	+	-	+	-	-	-	-
	(MLIT 2011b)	+	-	-	-	-	+	-
Disaster Prevention function	(MLIT 2011a)	+	+	-	-	-	+	-

Score: + =Data required

Score: - = Data not required

Table 3.4: Summary of existing evaluation methodology

Approach	Paper	Evaluation index	Probabilistic approach [a]	Area Isolation [b]	Socioeconomic impact [c]	Theoretical view point	Data requirement [d]	Calculation time [e]	Practical viewpoint [f]	One link failed area wise impact [g]
Accessibility	(Taylor, Sekhar et al. 2006)	Change in accessibility index	-	+	+	Vulnerable node, critical link	-	-	±	+
	(Sohn 2006)	Change in accessibility index	+	+	+	Critical link	±	±	±	+
Generalized travel cost	(Jenelius, Petersen et al. 2006)	Change in generalized travel cost	-	+	+	Important link and exposed municipality	-	-	±	+
	(Scott, Novak et al. 2006)	Network robustness Index	-	-	+	Critical link	-	±	±	+
	(MLIT 2011b)	Degree of weakness	+	-	+	Critical link	-	-	±	+
Disaster Prevention Function	(MLIT 2011a)	Detour ratio and level of links disaster protection function	+	+	+	Redundancy Disaster protection function	-	-	±	-

[a] Score: + =considered ; - = Do not considered
[b] Score += Considered ; - = Do not considered
[c] Score: + = considered; - = Do not considered
[d] Score: + = Higher ; - = lower and ± = medium
[e] Score: + = long time ; - = short time ± = Medium time
[f] Score: ± = Partly acceptable
[g] Score: + = Addressed ; - = Do not addressed

Table 3.5: Analysis of existing evaluation methodology form multidimensional viewpoint of positive and lacking perspective

SNo.	Viewpoint	(Taylor, Sekhar et al. 2006)		(Sohn 2006)		(Jenelius, Petersen et al. 2006)	
		Positive	Lacking	Positive	Lacking	Positive	Lacking
1	Socioeconomic Impact of network disruption	Evaluating the impact on accessibility of the service and facilities.	Has not considered how much population is affected.	Physical damage is converted to the damage on society.	Has not consider travel time.	The index; important link and exposed municipality are based on the change in generalized travel cost.	
2	Area Isolation	Complete loss in accessibility index caused area isolation.	The index is calculated through the concept one link failure at a time. Cannot explain more than 2 link failure condition.	Accessibility index of county (area) is calculated and area isolation represents the complete loss in the accessibility of an area.	Has not addressed multiple link failure condition	The value of importance, ∞ represents the area isolation	
3	Theoretical	Node vulnerability and link criticality is due to highest impact in the socioeconomic condition when road is closed.	Vulnerability is calculated without considering the adverse event.	Methodology has been proposed for the conversion of physical damage to the socioeconomic impact.		Important link and exposed municipality (Area) is calculated on the basis of the change in generalized travel cost.	The adverse event is not considered.
4	Practical	Measurable evaluation index.	Result is not plausible because it assumes every	Index is measurable and only links are selected from the 100	Level of threat based upon the depth and	Numerical value of importance is used to rank the	Result is not plausible because any

			shortest path fails at a time	year floodplain.	velocity of flood.	links.	adverse event is not considered
5	Data requirement	Very simple data is needed.	Traffic flow is not considered.	Complex data need GIS database.		Simple data are required	
6	Calculation time and process	Easy calculation process and less time consuming.	-	Complex calculation process need GIS experts		Medium level	
7	Area wise impact of single link failure	Accessibility index of each location is calculated if one link is failed		Index is calculated for each area(node) even in one link failure condition		Change in generalized travel cost is calculated for all OD pair after removing one link at a time.	
8	Probability of disaster	-	Has not considered any probability of the adverse event.	Links are selected from the 100 years floodplain and the probability of flood damage is multiplied by change in accessibility index.			Does not consider any probability of adverse event.

Table 3.6: Analysis of existing evaluation methodology form multidimensional viewpoint of positive and lacking perspective contd…..

SNo.	Viewpoint	(Scott, Novak et al. 2006)		(MLIT 2011b)		(MLIT 2011a)	
		Positive	Lacking	Positive	Lacking	Positive	Lacking
1	Socioeconomic Impact of network disruption	Total change in travel time due to failure of link which represents the socioeconomic impact.		Travel time is taken as socioeconomic indicator		Detour ratio is the important indicator for the evaluating redundancy	Population and other travel time parameter is not considered
2	Area Isolation		This index only calculates the total change in travel time under the one link failure. Does not calculate the locational index.	The index calculates the ratio of total travel time in a network after and before the disaster events.	Individual isolation of location is not analyzed.	Degree of isolation is analyzed by the level of link disaster protection function.	Numerical value of level of link disaster protection function.
3	Theoretical	Network robustness Index (NRI) To evaluate the critical importance of network link.	This methodology has not consider any adverse events in reality, index represent the link importance.	Degree of weakness is depends on the travel time.		Redundancy is analyzed through the detour ratio which is very clear indicator.	
4	Practical	Link importance calculated based on rerouting all the traffic after removing one link	The result only represents the link importance because it does not consider the adverse events.	Selection of link to be evaluated is practical.	Numerical value of disaster risk on the link.	Method is very practical in terms of redundancy and disaster protection function	It will be better if there is numerical value of level of threat from the disaster
5	Data requirement	Simple data		Simple data		Simple data	
6	Calculation time and process		Comparatively high calculation time, repetitive process and	Very easy calculation and less time consuming.		Easy and convenient calculation time.	

			need programming.				
7	Area wise impact of single link failure	Total impact on network (change in travel time) is calculated when particular link is failed		Total impact of travel time in a whole network is calculated.	Population or traffic volume is not considered.		Has not addressed one link failure area wise impact.
8	Probability of disaster		There is no any evidence of adverse event.	Although the numerical value of probability is not considered, links to be evaluated is selected under the probability of disaster	Numerical value of probability of adverse events	No numerical value of probability but the selection of link to be evaluated is based on the possibility of disaster.	Numerical value of level of threat is better parameter for the analysis

4. Evolution of practical evaluation methodology

As we discussed in the Chapter 3, existing methodologies yielded very important concepts and ideas but they lack to address the multiple link failure situation. Many of them do not consider the link closure event and their analysis are based on the assumption that only one link fails at a time.

This chapter presents the results of the computation based on the existing methodologies and some modification on them.

4.1. Model building process: computational experiment of existing methodologies in the real world.

We have selected two existing evaluation methodologies for the computational experiment in Tohoku region of Japan, where large number of links were closed after Great East Japan Earthquake on 11th March, 2011. **Error! Reference source not found.** shows the situation of National Highway and Expressway Network immediately after the Earthquake and Tsunami.

4.1.1. Existing methodology 1: Application of Accessibility Based Methods for Vulnerability Analysis of Strategic Road Networks

We compute the priority list of the closed link by using one of the methodology which we have analyzed in the chapter 3, The accessibility approach proposed by (Taylor, Sekhar et al. 2006).

Hansen integral accessibility index

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

Where,

A_i = accessibility index for origin node i

$B_{j=}$ Population of city j (service center)

x_{ij} = distance between i and j (or travel time can be taken)

$f(c_{ij}) = 1/x_{ij}$

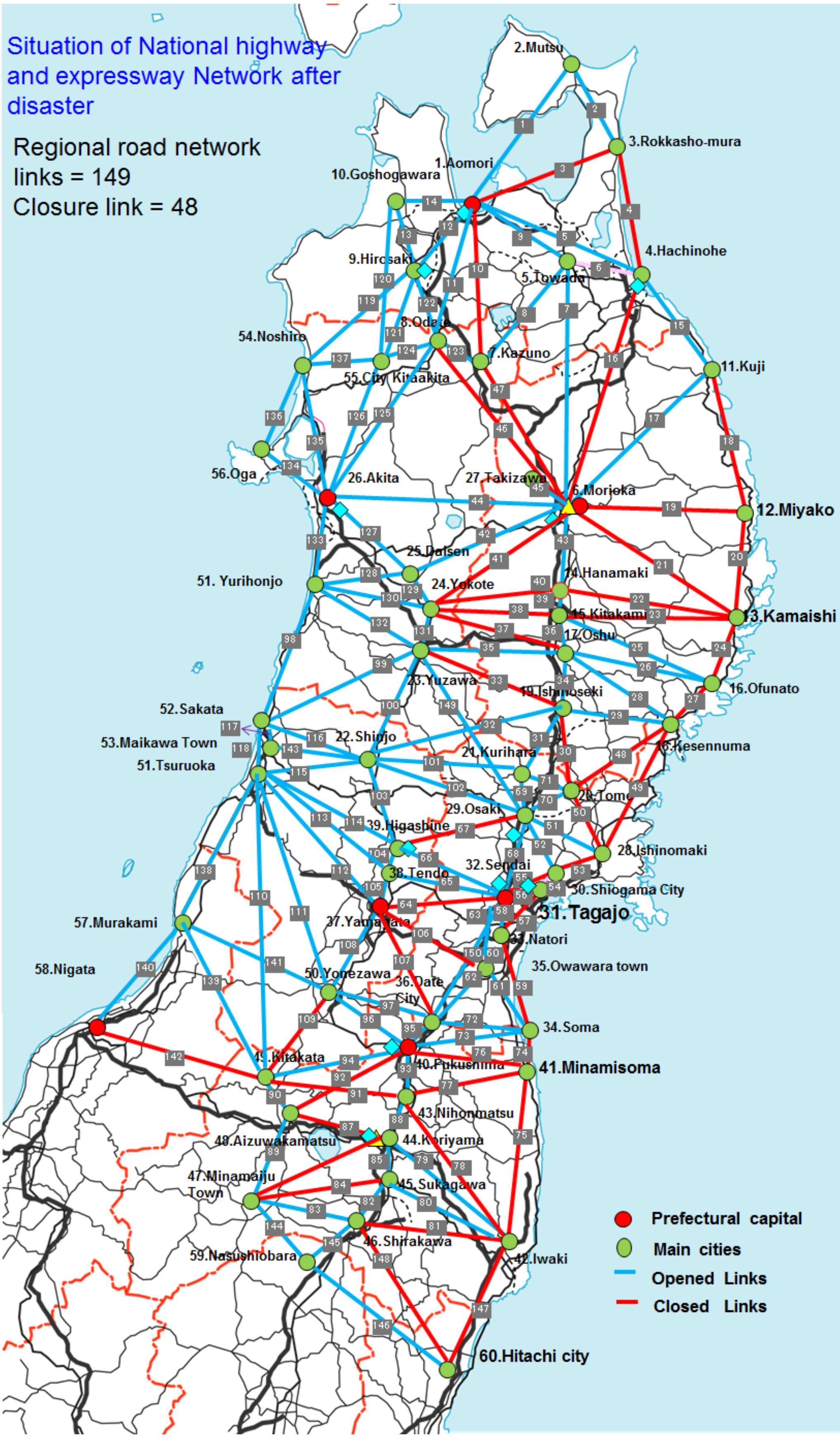


Figure 4.1: Situation of National Highway and Expressway network in Tohoku region immediately after Earthquake and Tsunami

Source: Road Bureau MLIT Japan

According to (Taylor, Sekhar et al. 2006), the calculation steps are as follows

1. Calculate the accessibility index of all origin node i with respect to the service center j at normal condition
2. Assume each link fails one at a time
3. Calculate the accessibility index of all origin node i with respect to the service center j at each link failure condition.
4. Calculate the percentage change in accessibility index for each link failure condition of each origin node.
5. Choose the link, which has highest percentage change in accessibility index as a top priority

By employing these 5 steps, we have got the priority list of the all links in Tohoku region's case. This methodology does not consider any closure event and evaluate the each link on the road network by assuming one link failure at a time. Basically, in any kinds of disaster event all links will not have same closure possibility. So the basic assumption of this methodology is not practical. This methodology does not calculate the cumulative effect of multiple link closure. The result shown in Appendix B is not plausible because the cities, Miyako, Minamisoma, Kamaishi, and Tagajo are disconnected from the National Highway and expressway network but this methodology does not prioritize the links which are important to connect these cities.

4.1.2. Existing methodology 2: Degree of weakness

In chapter 3,we have discussed about another methodology which is recently published manual from the Ministry of Land Infrastructure Transport and Tourism (MLIT 2011b). Here we have applied the same methodology for the identification of priority list of the closed link. The main important part of this methodology is: it assumes the links which can be closed in disaster situation or any closure event. The basic model and result of the Tohoku Region of regional road network are presented as follows;

The degree of weakness

$$\alpha_0^k = \frac{T_{02}^k}{T_{01}^k}$$

Where, α_0^k = the degree of weakness

$$T_{01}^{k} = \sum_{i}\sum_{j} t_{ij(n)}\delta_{ij(n)}$$

$$T_{02}^{k} = \sum_{i}\sum_{j} t_{ij(n)}\delta_{ij(n)}$$

T_{01}^{k} =Total travel time at normal condition

T_{02}^{k} =Total travel time after disaster event

$t_{ij(n)}$ = Total travel time from municipalities (i) to the nearest capital of the prefectures or expressway IC j (1) and the travel time from municipalities (i) to the neighboring municipalities' j (2).

$\delta_{ij(n)}$ = 1, the route from municipalities *i* to the nearest capital of prefecture or expressway IC j (1) and to the neighboring municipalities' j (2) can pass evaluated link (k).

$\delta_{ij(n)}$ = 0 do not pass the evaluated link (k)

The result shown in the Appendix C is not relevant, there is severe problem on the coastal side but the methodology prioritizes other link at top. And this result does not address the connectivity problem as discussed in the previous existing methodology .The links which are important for the connection of four cities and which were isolated from the national highway and expressway network are not prioritized at the top. The parameter; travel time, which this methodology considers is uncertain after the disaster event due to travel behavior of the user and other factor of the practical situation.

4.2. Computational experiment based on modification on existing methodology

First modification on the (Taylor, Sekhar et al. 2006)'s methodology

By considering the closed link on the network (the concept is taken from the (MLIT 2011b) methodology) and only evaluating (comparing) among closed links on the network based on the accessibility index. The result of the first modification seems more relevant as compared to previous original methodology but it does not emphasis the connection. There is no cumulative effect of the multiple link failure since it assumes one link failure at one time. Result is presented on the Appendix: D.

Second modification on the (Taylor, Sekhar et al. 2006)'s methodology

We found above two methodology cannot solve the multiple link failure condition therefore we make a computational experiment based on modification on (Taylor, Sekhar et al. 2006)'s model of accessibility index by considering the multiple link failure at a time.

$$A_i = \frac{\sum_{j=1} P_j / L_{ij}}{\sum_{j=1} P_j}$$

Where,

A_i = accessibility index for origin node i

$P_{j=}$ Population of city j (service center)

L_{ij} = distance between i and j

Here, we have taken distance only because travel time is uncertain at emergency condition.

Steps

1. Calculate the accessibility index of all origin nodes at normal condition.
2. Calculate the accessibility index of all origin nodes at worst condition. (During calculation of accessibility index the length Lij is calculated by using the Dijkstra's algorithm).
3. Calculate the accessibility index of all origin nodes for upgrading of each link one at a time.
4. Calculate the total accessibility index of all origin nodes (Network performance index) due to recovery of particular link.
5. Compare the links which have maximum network performance index and are selected as links to be upgraded first.
6. Deduct upgraded link from the worst case
7. Repeat the process until all links get prioritized.

The final result is presented in Appendix: E

This modification also cannot solve the connectivity problem because before opening the isolated node; methodology finds the other links in top priority. We conclude that there should be separate calculation procedure for connectivity and for network performance.

Any practical methodology should address the redundancy i.e. acceptable range of the alternative path. Recently, published manual (MLIT 2011a) gives an efficient measurement of redundancy evaluation, Which we have already discussed in chapter 3.

As a decision tools, the methodology should be sensitive for the less populated area and distance should be within some mobility range. Chapter 5 presents the efficient practical evaluation methodology which try to overcome the existing drawbacks.

5. The proposed evaluation methodology

5.1. Framework for development of Practical evaluation methodology

One of the most significant current discussions of road network evaluation methodology is its practicability. We have discussed in chapter 2 about current research on reliability of road network. In chapter 3rd, we have analyzed existing evaluation methodology based on the practicability. Also, we compute the result based on some existing methodology and some modification on them in Chapter 4. Those research have yielded wider application, theoretical concepts and ideas, however, they are yet in lack of practical application. Ideally, a methodology should meet the following requirements.

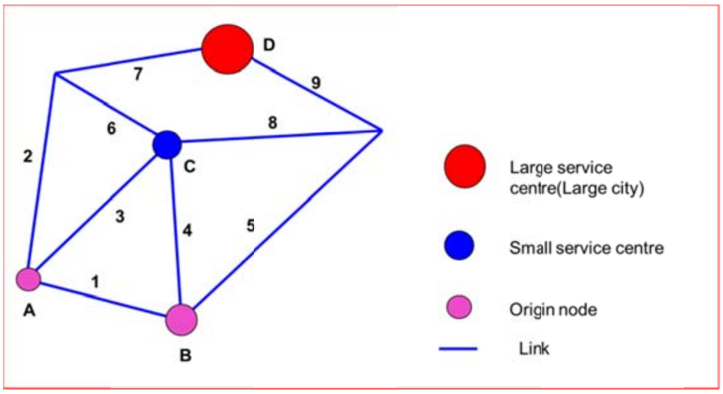
- A methodology should be based on easily available data.
- The easy calculation process and shorter computation time is preferable i.e. the methodology is preferable if it can be handled by each level of government authorities who are responsible for the different hierarchical structure of the road networks.
- Redundancy evaluation (the availability of alternative route) should be done during evaluation process.
- The methodology should be able to deal the condition of multiple link closure simultaneously.
- The methodology should primarily focus on network connectivity i.e. the links which are important to connect the isolated node should prioritize at top.
- The methodology should not be biased for the less populated and remote area.

To the best of our knowledge, there is not yet a methodology that covers all these requirements completely. We choose to use the accessibility index of an area which is given by (Hansen 1959), because this index is based on the population of the service center and distance. Also (Taylor, Sekhar et al. 2006) uses this index for the evaluation of road network, however they haven't considered various factor (please see chapter 3 & 4) because of which it is not so practical. But this methodology yielded the very useful concepts of socio-economic impact assessment of network disruption.

5.2. Definition of terms

Road Network

Road network consist of links, origin node and destination node. Figure 5.1 shows the example of road network



Origin node:

In our definition, origin node represents the city/ town and village which are dependent for various service facilities such as education, market, health etc. to the major city in the region. In Figure: 5.1 nodes A and B represent the origin node. In the model the letter, i represent the origin node.

Destination node:

Destination node represents the major city/ Metropolis in a region which attracts people from origin node for the education facilities, market (shopping etc.) health facilities (well facilitated hospitals with specialist) and other services which are only available in large cities. There is a hierarchy of the service center. As shown in Figure 5.1 C is the small service center and D is the large service center. In the proposed model the letter j represents the destination node.

Link:

In our definition, link represents road section connecting between two specific points. The specific points could be an origin node, destination node or only intersection or junction of two road section. In Figure 5.1 the blue line including number represents the road network link.

Path:

Path is a combination of one or more links which connects origin node to destination node. There could be one or more paths which connect same origin and destination node. In figure 5.1, for example the paths between origin node A to destination node D are the combination of links 2 - 7, 3-6-7, 2-6-8-9, 3-8-9, 1-4-8-9 and 1-5-8-9.

Shortest Path:

It is the path which has least travel time or distance connecting between origin node to destination node. There is only one shortest path existing between origin node to destination node. To identify the shortest path in a network, most efficient and popular algorithm Dijkstra algorithm can be applied. In the proposed model, Lij represents the shortest path.

Alternative shortest path:

It is the available shortest path between origin node and destination node when one or more path is disrupted in a network. Lija represents the shortest path in proposed model.

Redundancy:

Redundancy represents the backup alternative. In our model, if alternative path is available when one or more paths are disrupted then we can say network redundancy exists.

Accessibility

Accessibility refers to the ease of reaching opportunities for activities and services and can be used to assess the performance of a transportation and urban system (Chen, Yang et al. 2007). (Hansen 1959) defines the accessibility as a measurement of the spatial distribution of activities about a point, adjusted or the ability and the desire of people or firms to overcome the spatial separation. (Taylor, Sekhar et al. 2006) used the Hansen accessibility index for the evaluation of vulnerability of road network. The major goal of transport activity is to make access. Road transportation access refers to connection to the adjacent properties and limited access means minimal connection (Litman 2012).We are going to use the accessibility index for the network evaluation. The detail evaluation procedure is described in following section.

5.3. The model

5.3.1. Accessibility index of an area

Hansen accessibility index (Hansen 1959) gives a model for the accessibility index of an area with respect to the service centre.

$$_{i1}A_{j1} = \frac{S_{j1}}{T^{\alpha}_{i1-j1}}$$

Where,

i1Aj1= Accessibility measure of city/town i_1 with respect to service center 1

S_{j1}= Attraction value (size of the activities, number of jobs people etc.) of service center 1

T= Travel time or distance between i_1 and j_1

α= is an exponent describing the effect of travel time between the nodes.

Very simple measure of attraction value can be taken as a population of a service center because larger populated city has higher attraction from various kinds of opportunities.

If there is more than one hierarchy of service center available the index becomes

$$A_i = \frac{P_{j1}}{T^{\alpha}_{i1-j1}} + \frac{P_{j2}}{T^{\alpha}_{i1-j2}} + \ldots\ldots\ldots\ldots\ldots\ldots$$

Ai= accessibility index of origin node with respect the all service center

In general;

$$A_i = \sum_{j=1} P_j / T^{\alpha}_{i-j}$$

Since, travel time is uncertain at the emergency situation we consider the distance between origin node and service centre. We also take the value of α as 1. Finally, accessibility index of an area is taken as:

$$A_i = \sum_{j=1} P_j / L_{ij}$$

Lij is the shortest path between origin node i to service centre j. The shortest path is computed by using Dijkstra algorithm. Dijkstra algorithm is the most efficient and famous algorithm to compute the shortest path in graph.

5.3.2. Accessibility index of an area with population

Since (Hansen 1959) accessibility index gives the index of an area. It does not consider how many people are living in a particular area. Therefore, we simply improved the Hansen accessibility index here by considering the population of the origin node. The final model will be:

$$A_i = P_i * \sum_{j=1} P_j / L_{ij}$$

Normalized model of accessibility index of the population:

$$A_i = \frac{P_i * \sum_{j=1}^{n} P_j / L_{ij}}{P}$$

Where, P is the total population in the analysis area.

$$P = \sum P_i + \sum P_j$$

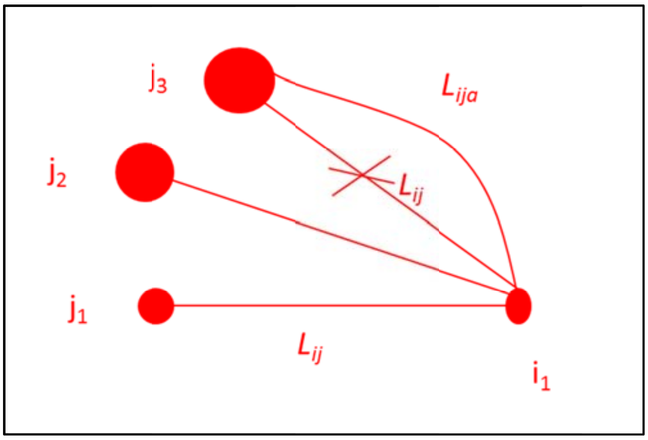
5.4. Vulnerability of road network:

Road network vulnerability represents various aspects and numerous research have been done for the vulnerability analysis, however, we here use the vulnerability for the availability of alternative path, when one or more links fail to connect the service centre from the origin node. Road network links are highly vulnerable if there is no any alternative option. Or alternative option is very long detour so that user doesn’t want to use the alternative path and he/she stops or postpones the journey.

5.4.1. Network Redundancy: availability of alternative path

The concept of redundancy is the spare capacity when there is any closure on the existing path the alternative path will continue to function. We have to check the availability of alternative path and acceptable limit of detour (lengthy).

Detour ratio



We have used the detour ratio for the measurement of the redundancy evaluation of available alternative shortest path when closure of one or more links in the shortest path. We took this very simple and practical measure for the redundancy evaluation from recently published manual of Ministry of Land, Infrastructure, Transport and Tourism (MLIT) Japan (MLIT 2011a).

$$DR_{ij} = \frac{L_{ija}}{L_{ij}}$$

Where

Lij= shortest path between i and j

Lija = alternative shortest path when one or more links fail in the shortest path

In every step shortest path is computed by Dijkstra's algorithm.

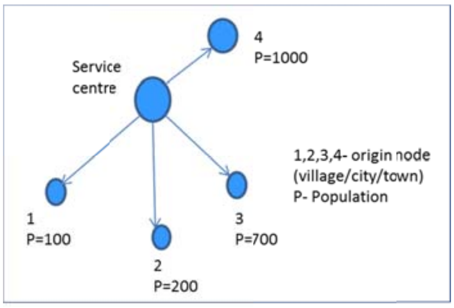
5.5. Sensitivity analysis

In our model the main variable are population of the origin node and length between the origin node and service centre. In reality, from our model, the city/village/town which have higher population and nearer from the major city centre is prioritized first. When developing the policy decision tools, sometimes the result is not relevant. So we need to have a bench mark for the population and distance. Those bench marks for population and distance we named here as critical population and critical distance.

To identify the bench mark value we proposed doing sensitivity analysis for each case. Sensitivity analysis is employed to investigate the turning importance of each parameter (Saltelli, Chan et al. 2008).So following section analyse the population sensitivity and distance sensitivity.

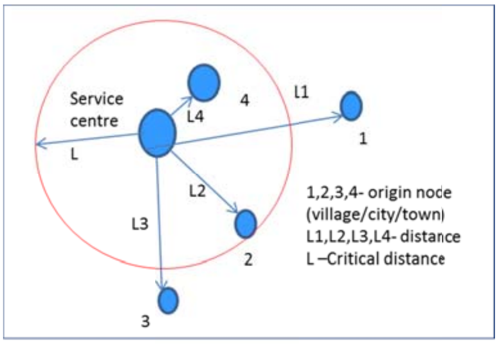
5.5.1. Critical population of an area

Critical population of an area is derived from the sensitivity analysis. For example, as shown in Figure 5.3 the population in the origin node 1 and 2 are very less but from the political view point, policy maker should give equal focus up to certain value. But, the question is how much population could be the bench mark for the less populated area? For example if we get the critical population 500 from the sensitivity analysis than we can say the village 1 and village 2 are equally focused from the policy maker. In our model the index will be higher if population is higher so from this sensitivity analyses the less populated area will be focused equally as city having populations of 500. We can say this kind of policy is more justifiable than just comparing the population of an area.



5.5.2. Critical distance to the service center

In our model the cities/village/town which is near from the major service centre will gain the highest value of accessibility. So from the policy maker's side if there is some threshold value of distance i.e. in a boundary of some mobility range it is treated equally. For example as shown in the Figure 5.3; the critical distance is L, so village 2 and 4 will be equally focused for the length below L. This analysis implies that in a fixed distance we should provide equal focus for all city/village and town.



5.5.3. Acceptable value of detour ratio

The detour ratio i.e. the lengthiness of alternative path mainly depends on the user's choice. In a developed country like japan it should be lower than that of developing country Nepal. We are trying arbitrarily in a calculation process and observe how much will the result change. And we fix the value of detour ratio. The detail observation including the result is explained in each case in Chapter 6.

5.6. The solution algorithm for the prioritization of road network links

The major interesting part of this research is prioritizing the links in two stages. The first stage identifies the important link for the network connection and second stage identifies the important links to increase the network performance. A detailed step by step computation processes is presented as follows:

5.6.1. Network performance at normal condition

Step 1

Identify the shortest distance (Lij) between Origin node and each service centre by using Dijkstra's algorithm.

Compute the accessibility index of origin node with respect to all service centres at normal condition

$$A_i\ (normal) = \frac{Pi * \sum_{j=1} P\,j/L\,ij}{P}$$

Step 2

Compute the total network performance index

$$\mathrm{NPI} = \sum \mathrm{A}i$$

Step 3

Identify the Critical distance (CRD) and Critical Population (CRP) with the help of sensitivity analysis. A different value of Critical distance and critical population is adopted in the equation in the accessibility index at normal condition. Network performance index for each Critical Distance (CRD) and Critical population (CRP) is calculated. A tendency curve for both CRD and CRP is plotted and identify the critical value, where curve changes dramatically.

$$\mathrm{NPI}^{CRD} = \sum \mathrm{A}_i^{CRD}$$

$$\mathrm{NPI}^{CRP} = \sum \mathrm{A}_i^{CRP}$$

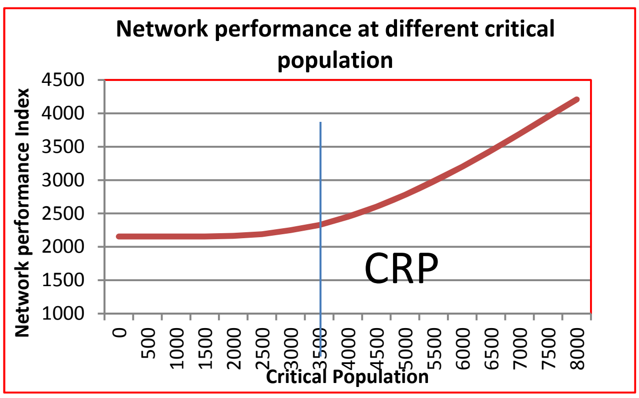


Figure 5.5: Example curve for Critical Population(CRP)

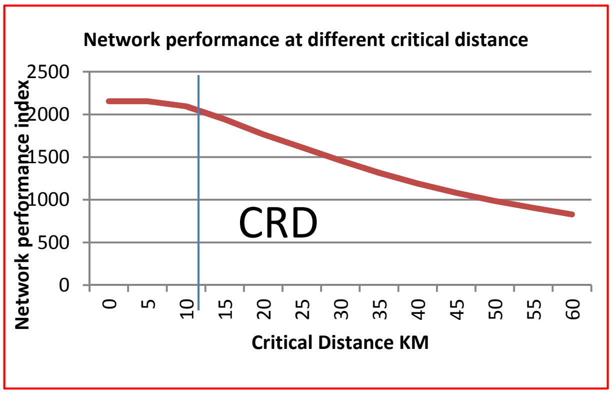


Figure 5.6: Example curve for Critical Distance (CRD)

Step 4

Repeat again step 1 and 2 to compute the Network Performance Index including critical population and critical distance

$$A_i \ (normal) = \frac{Pi * \sum_{j=1} Pj/Lij}{P}$$

Lij = { Critical distance (CRD) if Lij<=Critical distance
Lij if Lij> critical distance

Similarly,

Pi= { Critical population (CRP) if Pi<= Critical population
Pi if Pi> Critical population

$$\text{NPI}_{normal} = \sum \text{A}i$$

5.6.2. Network performance at worst condition

Step 5

Identify the available shortest path Lija (if one or more link close on the network at normal condition) from origin node i to service centre j by using Dijkstra's algorithm. Compute the accessibility index of all origin nodes at worst (Link closure) condition

$$A_i \ (Worst) = \frac{Pi * \sum_{j=1} P\,j/L\,ij\,a * \delta\,ij}{P}$$

if $A_i \ (Worst)$=0 Isolated Node (i)

$if\ Ai(Worst) > 0$ Connected Node (i)

$$\delta_{ij} = \begin{cases} 1 & \text{if } DR_{ij} <= \text{Acceptable limit} \\ \infty & \text{if } DR_{ij} > \text{Acceptable limit} \end{cases}$$

Where,

Detour Ratio $DR_{ij} = \dfrac{L_{ija}}{L_{ij}}$

$$Lij = \begin{cases} \text{Critical distance (CRD) if } Lij <= \text{Critical distance} \\ Lij \text{ if } Lij > \text{critical distance} \end{cases}$$

Similarly

$$Pi = \begin{cases} \text{Critical population (CRP) if } Pi <= \text{Critical population} \\ Pi \text{ if } Pi > \text{Critical population} \end{cases}$$

Step 6

Compute the Network performance index at worst condition

$$NPI_{worst} = \sum Ai_{worst}$$

5.6.3. Priority list of links for Network Connection

Step 7

In this step we have two different set of closed (impassable) and opened (passable) links. For the analysis, all impassable links are tried as a temporary opened links at a time.

Identify the available shortest path Lija from isolated origin node i to service centre j for each link's returned case by using Dijkstra's algorithm.

Compute the accessibility index for all isolated node (which are identified in step 5) on returning of each closed link k.

$$A_i^k = \frac{Pi * \sum_{j=1} Pj/(L\,ij\,a * \delta\,ij)}{P}$$

$if\ A_i^k$=0 Isolated Node (i)

$if\ A_i^k > 0$ Connected Node (i)

$$\delta_{ij} = \begin{cases} 1 & \text{if } DR_{ij} \text{ <=Acceptable limit} \\ \infty & \text{if } DR_{ij} \text{ >Acceptable limit} \end{cases}$$

Where,

Detour Ratio $DR_{ij} = \dfrac{L_{ija}}{L_{ij}}$

$$Lij = \begin{cases} \text{Critical distance (CRD) if Lij<=Critical distance} \\ \text{Lij if Lij> critical distance} \end{cases}$$

Similarly

$$Pi = \begin{cases} \text{Critical population (CRP) if Pi<= Critical population} \\ \text{Pi if Pi> Critical population} \end{cases}$$

Step 8

Compute the Network performance index after returning of each link k

$$NPI^k = \sum A_i^k$$

Step 9

Select the link k at top priority which has maximum Network performance index

Step 10

Deduct the selected link k from the set of the closed link and take as a passable (opened) link for the next iteration

Step 11

Repeat step 7 to 10 until all nodes are in connection i.e. all A_i^k will be greater than zero.

5.6.4. Priority list of links to increase the Network performance

From above calculation, after preparing the list of links for network connection, still there may be remaining list of closed links. To rank the remaining links the following steps are suggested.

Step 12

For the analysis, all impassable links are tried as a temporary opened links at a time. Identify the available shortest path Lija from all origin node i to service centre j for each link's returned case by using Dijkstra's algorithm.

Compute the accessibility index of all origin nodes on returning of each closed link k.

$$A_i^k = \frac{Pi * \sum_{j=1} P\,j/(L\,ij\,a * \delta\,ij)}{P}$$

$$\delta_{ij} = \begin{cases} 1 \text{ if } DR_{ij} \text{ <=Acceptable limit} \\ \infty \text{ if } DR_{ij} \text{ >Acceptable limit} \end{cases}$$

Where,

$$\text{Detour Ratio } DR_{ij} = \frac{L_{ija}}{L_{ij}}$$

$$\text{Lij} = \begin{cases} \text{Critical distance (CRD) if Lij<=Critical distance} \\ \text{Lij if Lij> critical distance} \end{cases}$$

Similarly

$$\text{Pi=} \begin{cases} \text{Critical population (CRP) if Pi<= Critical population} \\ \text{Pi if Pi> Critical population} \end{cases}$$

Step 13

Compute the Network performance index after returning of each link k

$$NPI^k = \frac{\sum A_i^k - NPIworst}{NPInormal - NPIworst} x100\%$$

Step 14

Select the link k at top priority which has maximum Network performance index .

Step 15

Deduct the selected link k from the set of closed links.

Step 16

Add the selected link k to the set of passable links.

Repeat step 12 to step 16 until the closed links get finished.

Finally priority list of links is prepared as the links which are important for network connection giving top priority and links which are important to increase the network performance as second priority.

5.6.5. Network performance at any time

Step 17

Identify the available shortest path Lija (if one or more link close on the network at normal condition) from origin node i to service centre j by using Dijkstra's algorithm.

Compute the accessibility index of all origin nodes at any time.

$$A_i^t = \frac{Pi * \sum_{j=1} P\,j/(L\,ij\,a * \delta\,ij)}{P}$$

$if\ A_i^t$=0 Isolated Node (i)

$if\ A_i^t > 0$ Connected Node (i)

$$\delta_{ij} = \begin{cases} 1 & \text{if } DR_{ij} \text{ <=Acceptable limit} \\ \infty & \text{if } DR_{ij} \text{ >Acceptable limit} \end{cases}$$

Where,

Detour Ratio $DR_{ij} = \frac{L_{ija}}{L_{ij}}$

$$\text{Lij} = \begin{cases} \text{Critical distance (CRD) if Lij<=Critical distance} \\ \text{Lij if Lij> critical distance} \end{cases}$$

Similarly

$$Pi = \begin{cases} \text{Critical population (CRP) if } Pi <= \text{ Critical population} \\ Pi \text{ if } Pi > \text{ Critical population} \end{cases}$$

Step 18

Network performance at any time

$$NPI^{t} = \sum A_{i}^{t}$$

Percentage achievement in network performance at any time

% NPI= $NPI^{t} / NPInormal$

Prepararion of priority list of road network link considering the multilpe link closure condition simulteneously

FLOW CHART

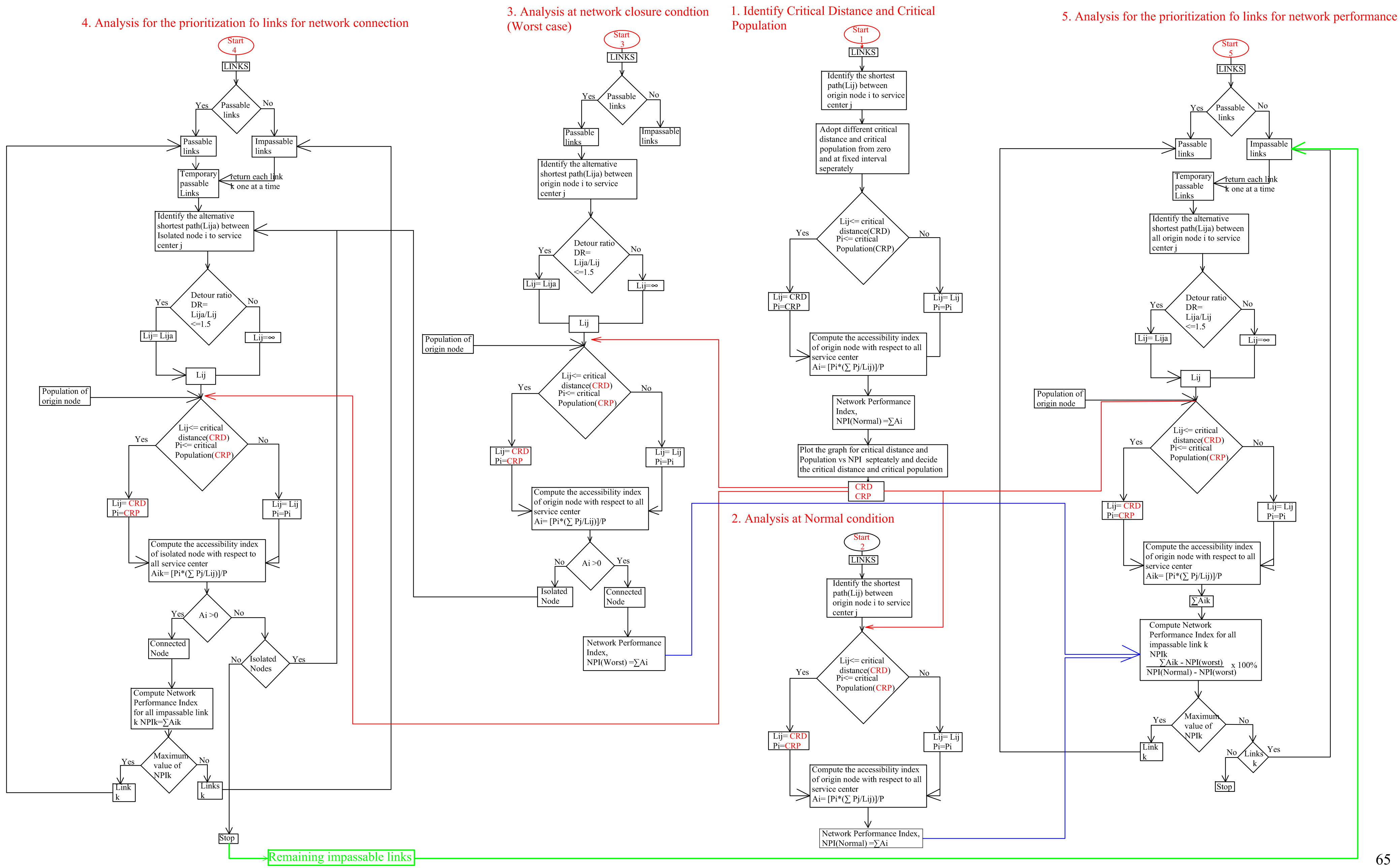


Figure 5.7: Flow Chart for detail calculation procedure

6. Application of proposed evaluation methodology

Road network can be unreliable due to natural disaster such as earthquake, flood, landslide and adverse weather. We mentioned at the beginning of this thesis about the real practical problem of road network closure. The main interesting aspect of this methodology is its application for the evaluation of closed link in any kinds of closure events, any level of road network hierarchy. We have applied the proposed evaluation methodology in regional road network closure in Japan and rural road network closure in Nepal.

6.1. Japan's case study

In Japan, road network are closed mainly due to natural disaster like earthquake, tsunami, typhoon and landslide. In the large scale disaster like Tohoku Earthquake and Kobe Earthquake there caused severe problem on the road network. Many sections of national highway, expressway, prefectural road and municipal road were closed. Many areas were isolated and connectivity became severe problem.

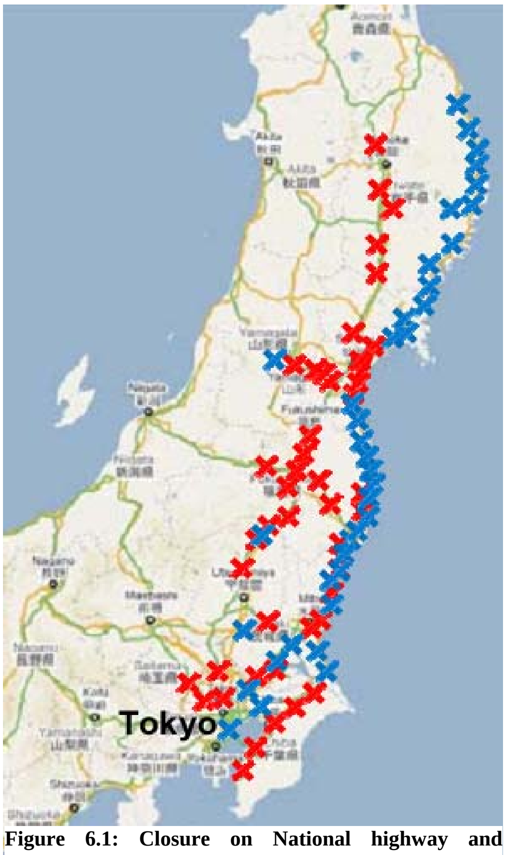


Figure 6.1: Closure on National highway and Expressway,
Source: (Kawasaki 2011)

On 11th March, 2011 'The Great East Japan Earthquake' of magnitude 9 on the Japan Meteorological Association scale caused the severe impact on the Tohoku region's life. Massive tsunami generated and height reached almost 40m which took more than 15000 lives, more than 4000 people were missing and over 5900 people were injured. There was heavy loss of life and property. More than 115,000 buildings were completely collapsed and over 160,000 buildings were half collapsed. Road network failure affects the wide area. After disaster, 15 expressway routes and 69 sections on the national highway were closed. Numerous section of prefectural and municipal roads were closed too(Kawasaki 2011).

6.1.1. National highway and expressway in Tohoku region immediately after earthquake

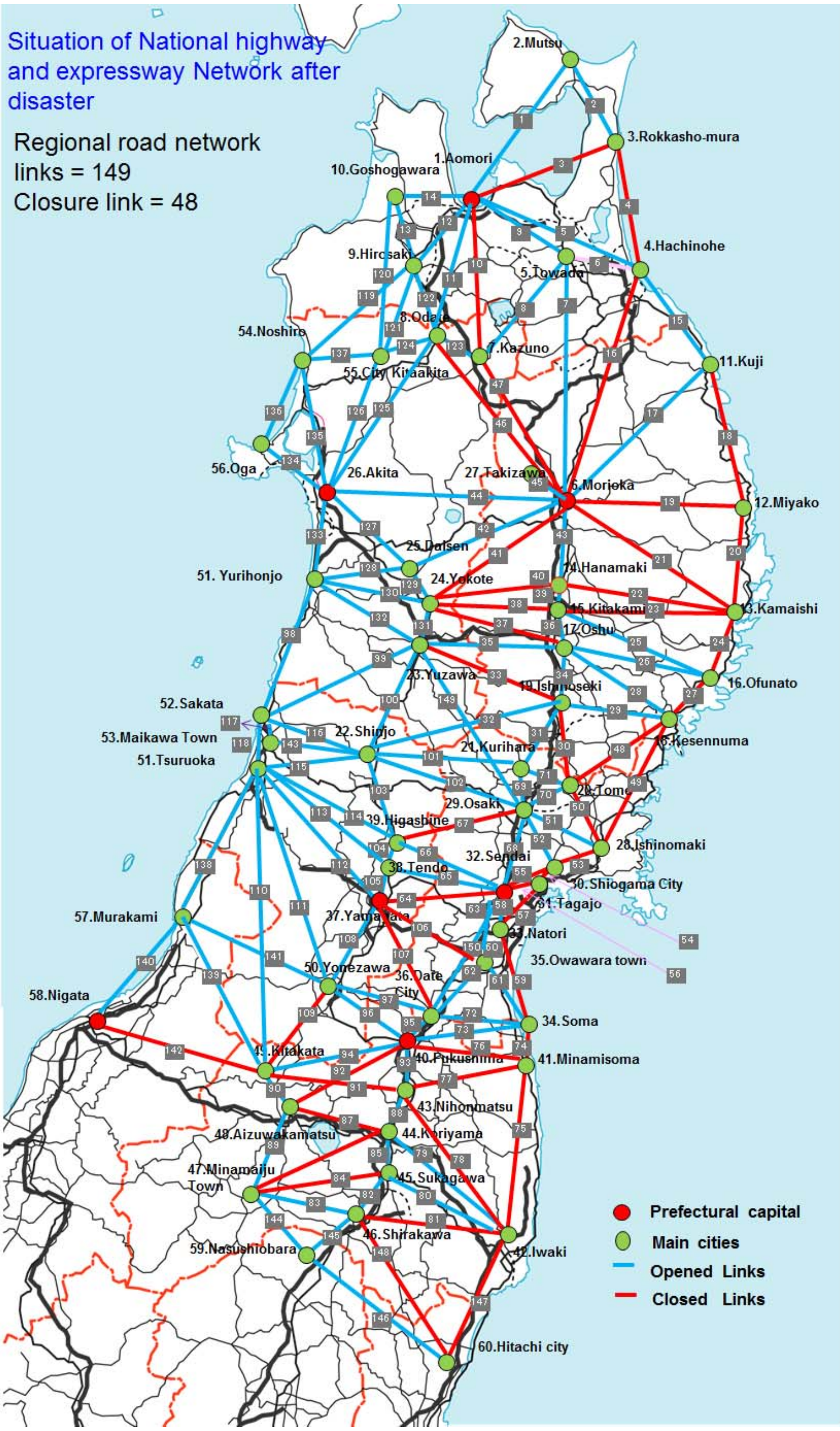


Figure 6.2: Situation of Expressway and National highway network in Tohoku region immediately after earthquake

Source: Road Bureau MLIT Japan

The National Highway and Expressway network in Tohoku region (as shown in Figure 6.2) is taken as the case study for the application of the methodology in this section. Among the 149 links; 48 links were closed immediately after earthquake and tsunami. The blue line represents opened links and red line represents the closed links. Most of the links which connect to coastal city were damaged by the tsunami and 4 cities were isolated from the national highway and expressway connection. We consider here link as a road section connecting between city to city and city to prefectural capital through national highway and expressway. Prefectural capital and regional centre Sendai (the large city in the region) is taken as destination node (service centre) and other cities and town are taken as origin node.

Our data analysis consist only the national highway and expressway network. There was very severe problem of connection which can be found from the viewpoint of the prefectural road or municipal road network. This methodology can be used by each government authority for the road network under their responsibility. So here we take an example of regional road network under the road bureau of the Tohoku Region.

6.1.1.1.Sensitivity Analysis: Identification of critical distance and critical population

As we discussed in the section 5.4 of Chapter 5, we perform the sensitivity analysis. In the calculation process we assume different value of critical distance and critical population in fixed interval. The methodology takes the critical value; if the real data is less than the critical value otherwise it takes original value.

Critical Distance:

Figure 6.3 shows the network performance index at different distance when critical population is zero.

To verify the identified value of critical distance we have plotted the curve of network performance index for different population (Figure 6.4). We got the curve almost parallel so we decide to take the critical distance as 15 KM where the tendency of curve has changed dramatically.

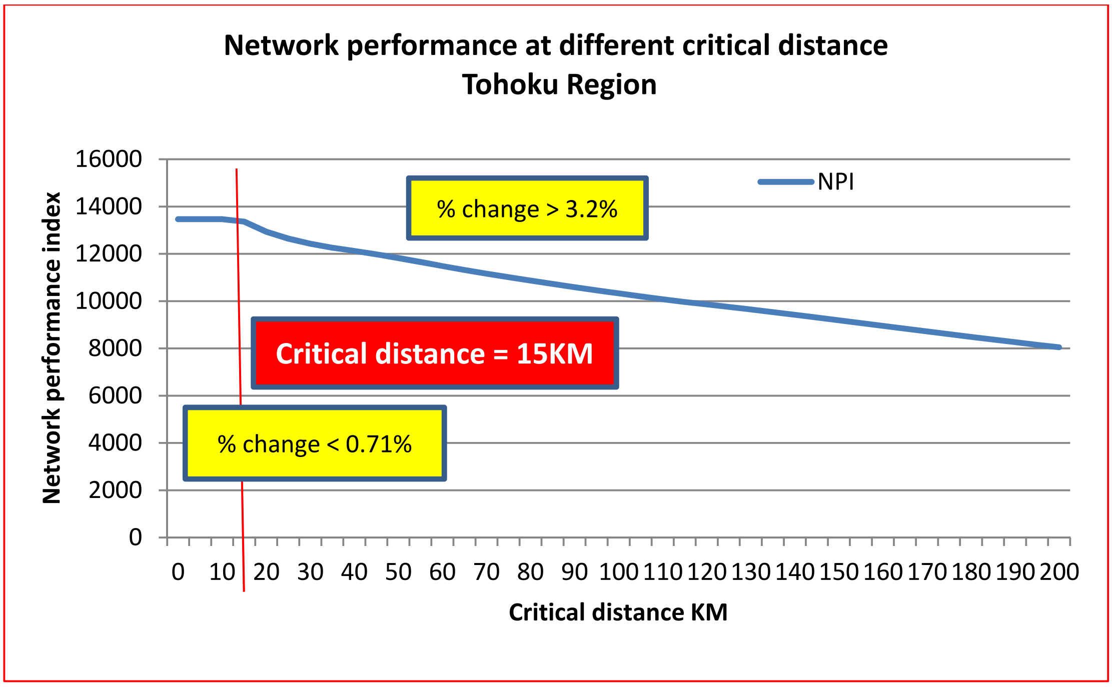


Figure 6.3: Critical distance VS Network performance index curve when critical population is zero (Tohoku region, Japan)

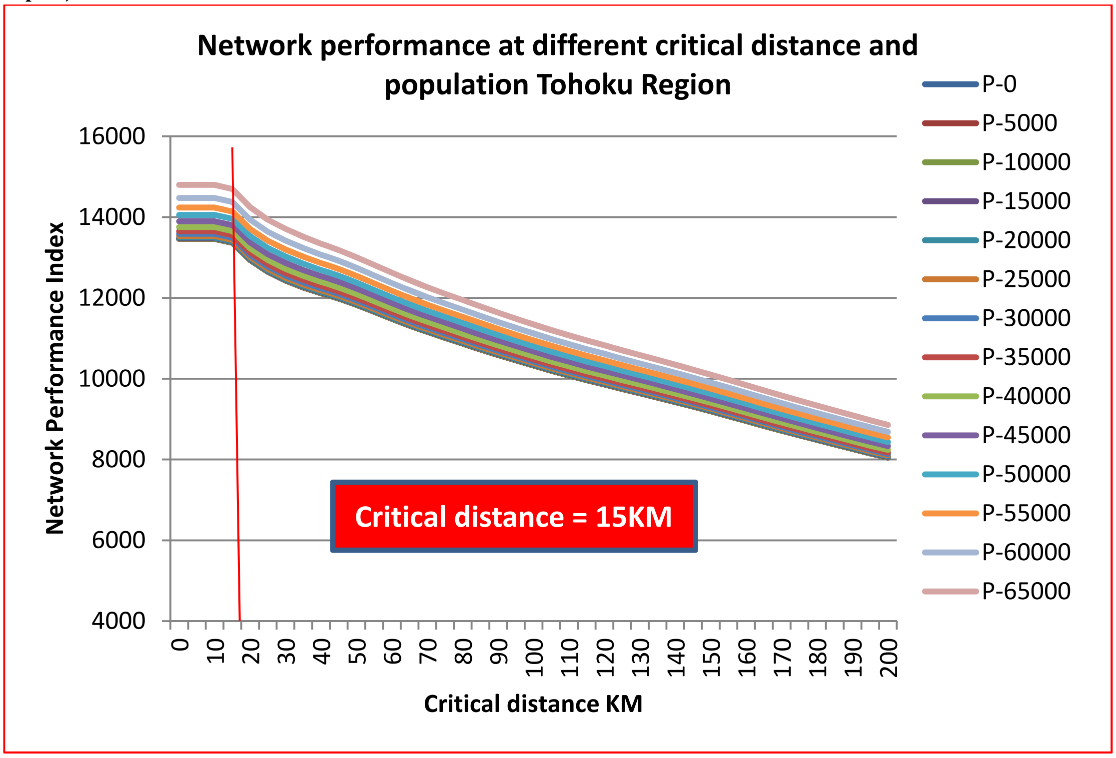


Figure 6.4: Tendency curves of the network performance index at different critical distance and different population (Tohoku Region, Japan)

Critical Population:

During calculation of network performance index, different value of critical population is adopted. The city population, which is less than critical population is taken as equal to critical population and the city population which is higher than critical population is taken as actual city population. We calculate the network performance index for the different value of critical population at critical distance zero and plot the curve as shown in Figure 6.5.From the tendency curve we decide the critical population as 40,000; the point where tendency curve change dramatically.

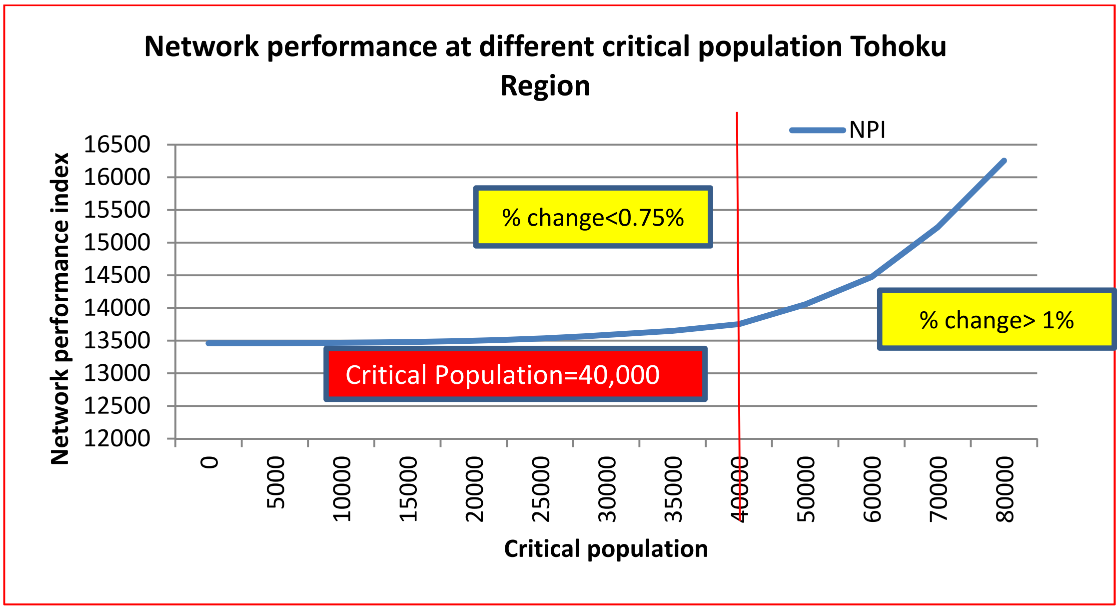


Figure 6.5: Critical population vs. Network performance index curve when critical distance is zero (Tohoku Region)

We have also plotted the curves of different population vs network performance index for different critical distances. Figure 6.6 shows the tendency curve of critical population vs network performance index for different critical distances. The patterns of curves are almost parallel so we can say the selected value of critical population 40,000 is correct.

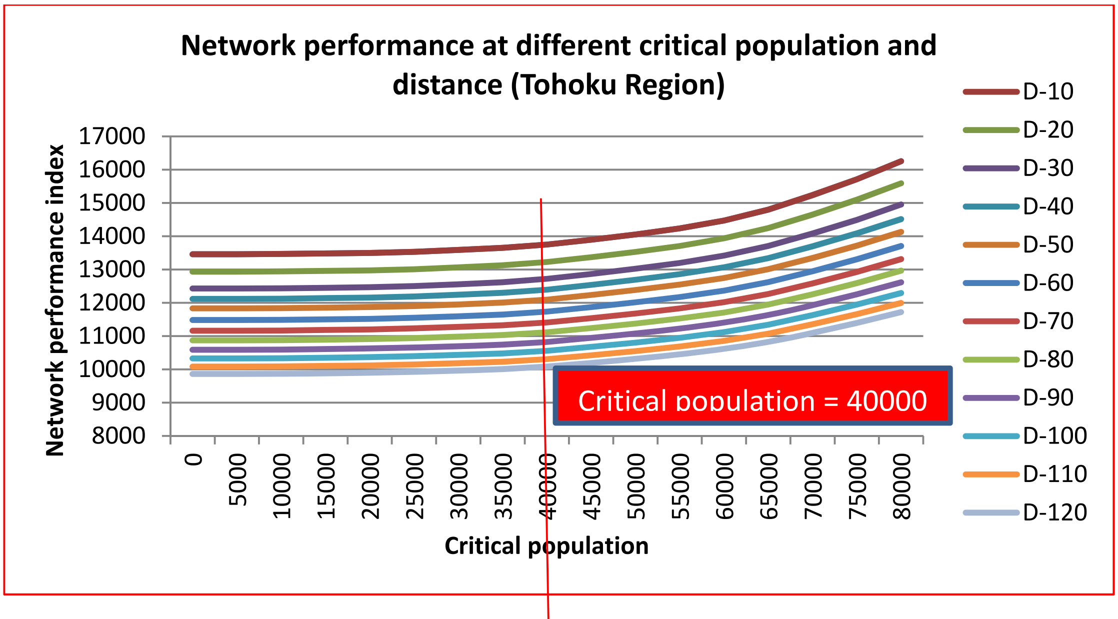


Figure 6.6: Tendency curves of the network performance index at different critical population and different critical distance (Tohoku Region Japan)

6.1.1.2.Identification of Isolated node and important link to connect them

As we explained in the chapter 5 we applied the solution algorithm in the Tohoku regional road network step by step. At first the algorithm identifies the isolated node. And links, which are important to connect the isolated node on each iteration. One link is identified through first iteration and prioritized at the top. The link which is identified on first iteration is treated as recovered link for the next iteration. As shown in the Figure 6.7 all links are assumed as a recovered link individually; compare their performance in the network after temporarily recovered and select one link which has highest performance index at top priority.

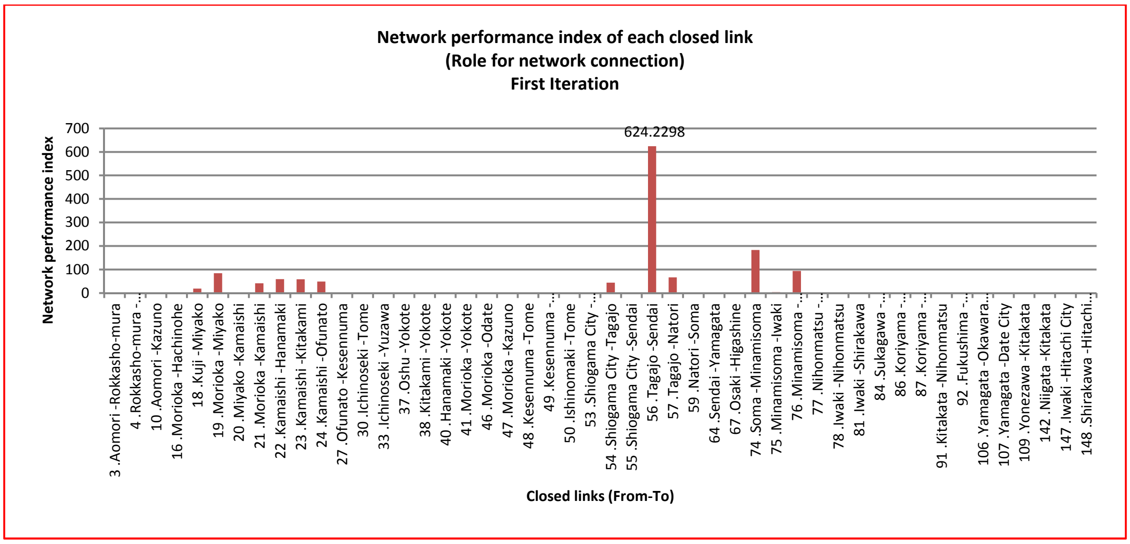


Figure 6.7: Comparative value of Network performance index (NPI) after assumption of recovery of each closed link; at first iteration

The Figure 6.7 shows, the link which connects the isolated city Tagajo to Sendai (the largest city in the region) and has highest Network performance index selected as top priority.

In the second iteration as shown in Figure 6.8 the link which is prioritize at top is treated as a recovered link (opened link) and calculate the network performance index. The value of network performance index will include the cumulative effect of the previous identified link as shown in Figure 6.8. The link shown by blue bar is treated as recovered link. The link which connects the isolated city MinamiSoma to Soma has highest network performance index and is prioritize at second position.

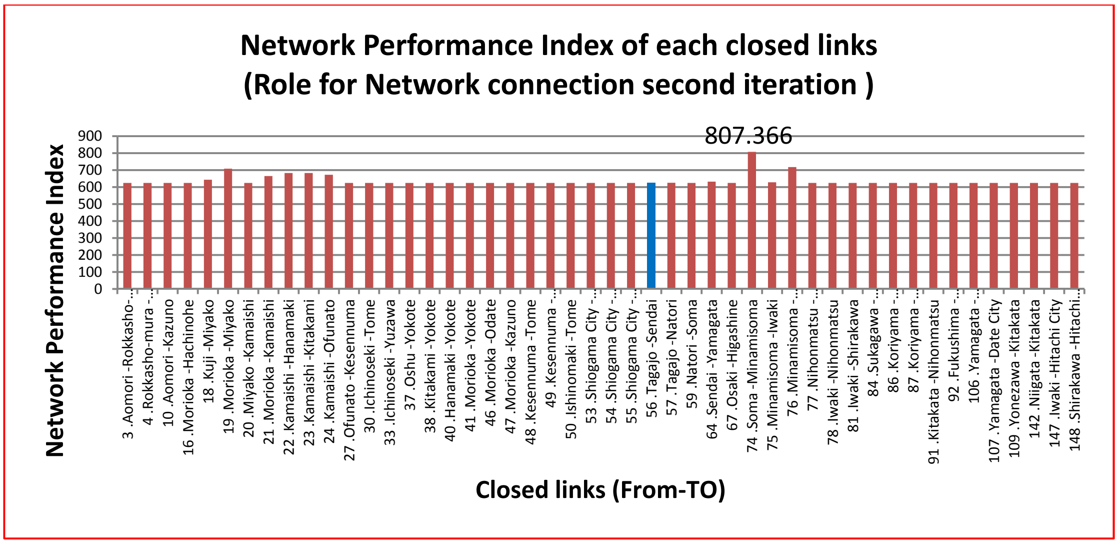


Figure 6.8: Comparative value of Network performance index (NPI) after assumption of recovery of each remaining closed link at second iteration

Similarly in the third iteration previous two links is assumed as recovered link and third priority link is identified as Morioka to Miyako, connect the isolated city Miyako, which has highest network performance index as shown in Figure 6.9. This process is repeated until all isolated node get connected. Figure 6.10 presents the final result in map including links with priority number for the connection of isolated node.

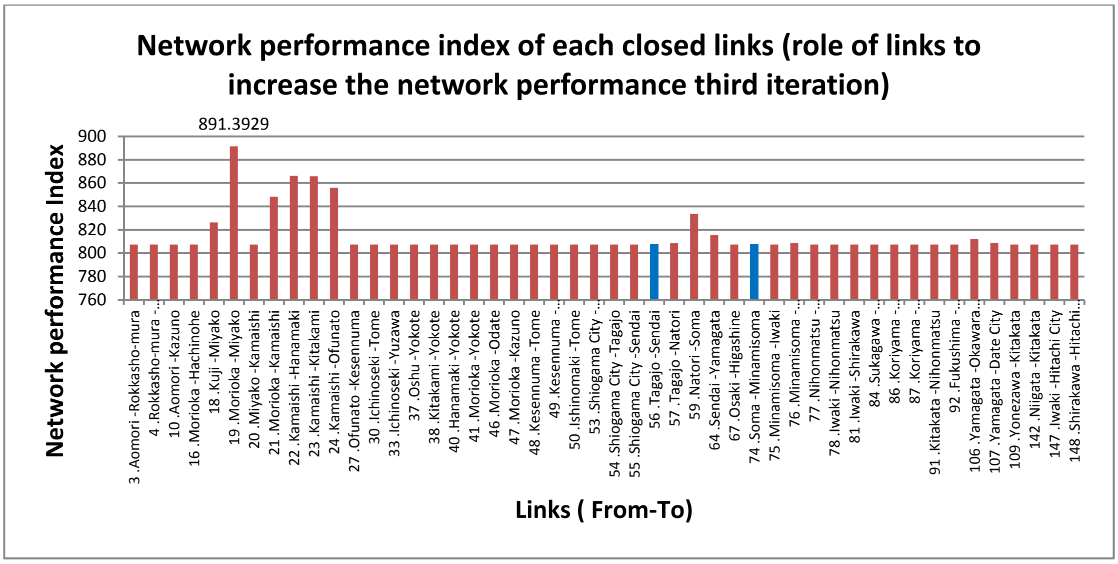


Figure 6.9: Comparative value of Network performance index (NPI) after assumption of recovery of each remaining closed link at third iteration

6.1.1.3.Identification and prioritization of links to increase network performance after achieving the network in connection

In the previous section we have analyse the link which are important for the network connection. There are 4 links which have been selected for the network connection.

Figure 6.10: Map with priority number of links important for the network connection (Tohoku Region)

Figure 6.12 represents the comparison of result with Japanese government decision in Tohoku region. The result is interestingly matched with the decision of reconstruction support expressway from Miyako to Morioka and Kamaishi to Hanamaki decided by MLIT, Japan in August 2011, after disaster (MLIT 2011c).

After achieving the network connection, out of 48 closed links; 44 links still remain in closed condition. As we proposed the methodology and calculation steps in chapter 5, network performance indexes are calculated for each link by assuming each link recovered one at a time. Figure 6.11 shows the comparative chart of the closed links with network performance index (which link has how much percentage improvement in the network performance index if recovered at first). Two links Shiogama City to Tagajo and Shiogama City to Sendai show the equal highest value. We further compare these two links based on travel time; Shiogama City to Tagajo has shortest travel time so we choose link Shiogama City to Tagajoo as top priority and Shiogama city to Sendai as second priority.

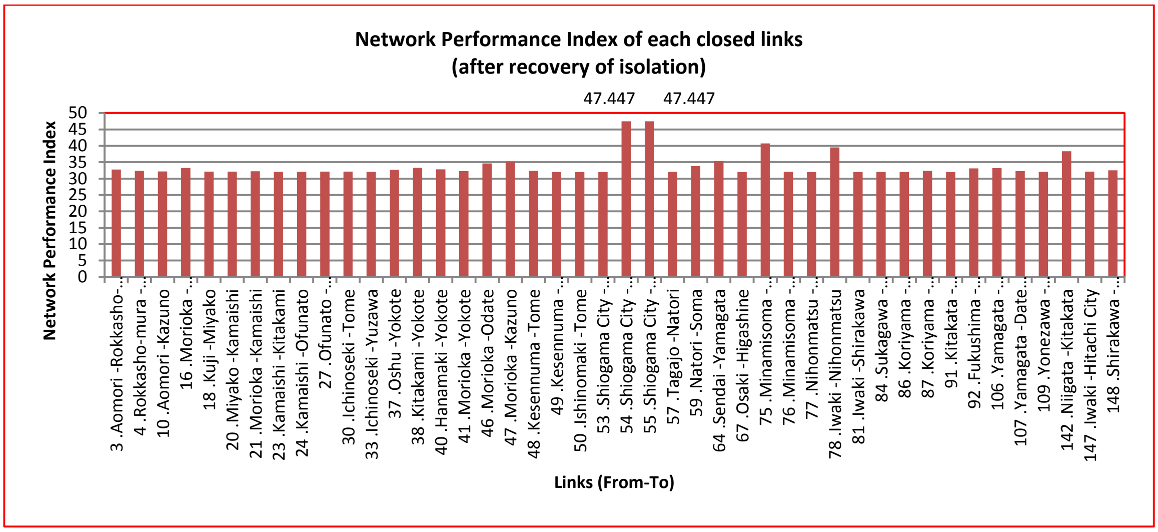


Figure 6.11: Comparative chart of the closed links after achieving the network connection based on percentage improvement on network performance index (first iteration)

The calculation process will repeat until all remaining links are recovered. Following Figure 6.13 and Appendix: F shows the final priority list of the closed road network link in Tohoku region including links which are important for the network connection as a top priority and links which are important to increase the network performance.

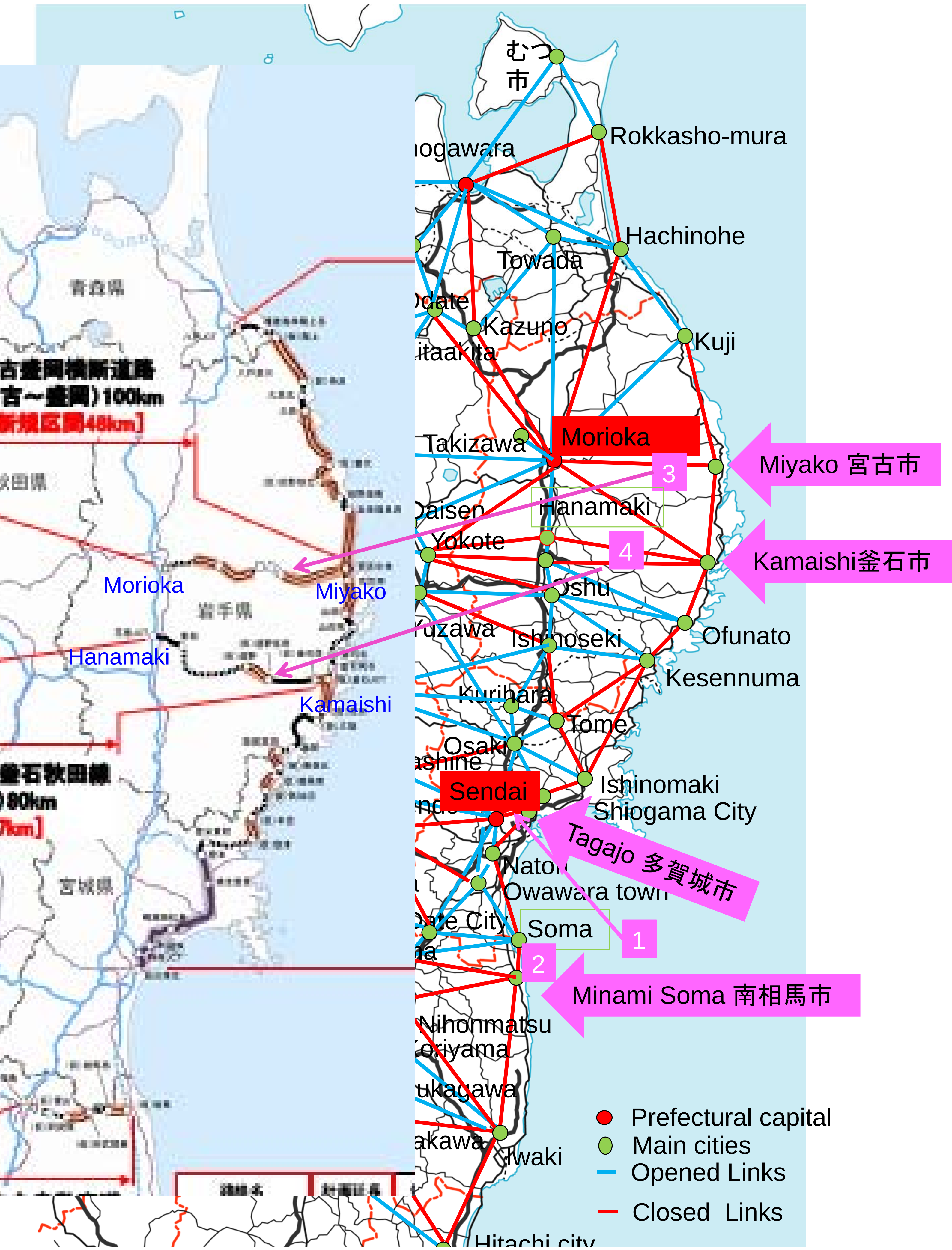


Figure 6.12: Result comparison with Japanese Government Decision

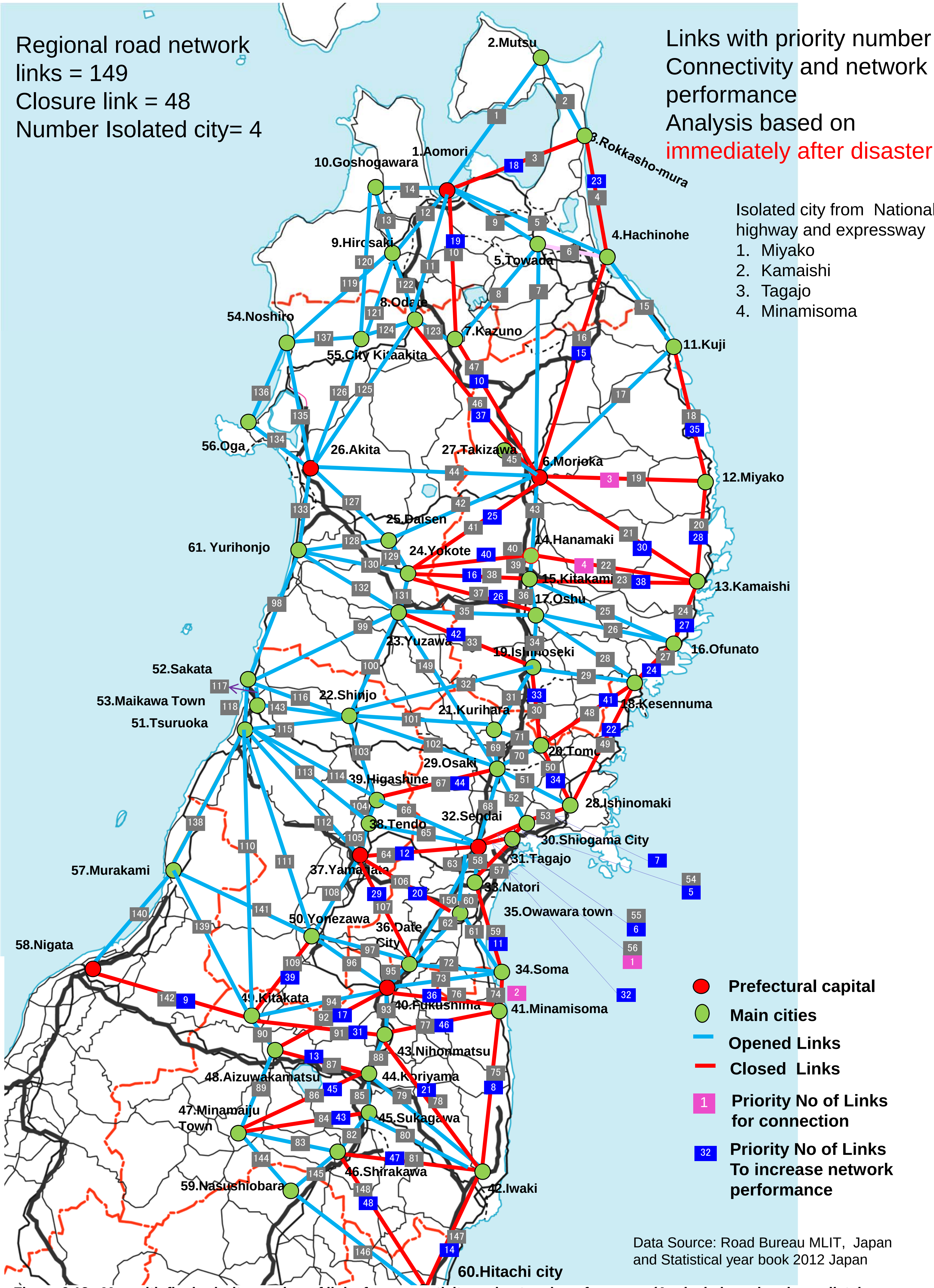


Figure 6.13: Map with final priority number of links for connectivity and network performance (Analysis based on immediately after disaster , Tohoku Region Japan)

Decision of Detour Ratio: As we discussed in section 5.5.3, we compute the result for the two different values of detour ratio as 1.5 and 2. The result shown in figure 6.13, is computed at detour ratio 1.5. Appendix F shows the final priority list of closed links for the improvement projects including for network connection and network performance at detour ratio 1.5. Appendix G shows the final priority list of closed links for the improvement projects at detour ratio 2. We found there is no change in the priority number for the network connection while few priority number changes for the network performance. After achieving the network connection the detour ratio 1.5 is suitable for the redundancy evaluation. Hence, we would like to recommend the acceptable value of detour ratio as 1.5 for this case.

6.1.2. National highway and expressway in Tohoku region one week after earthquake

Basically our analysis does not cover any level of hazard in the links; we just consider that the links are close or not. In previous section we took the information of Tohoku region immediately after the earthquake and Tsunami. Some of the road section can open within one week or within two days and some of the road section need long time for the opening. If we separate the links which can open within one week and links which needs long time we can allocate the resource in the same way. Figure 6.15 shows the priority number of the links for the improvement based on the information of road network links one week after earthquake and tsunami. The priority list of the links is presented in Appendix H.

6.1.3. Network performance during reconstruction

We have use the model to identify the percentage achievement of network performance index during reconstruction time. Network performance index is calculated at any time by upgrading

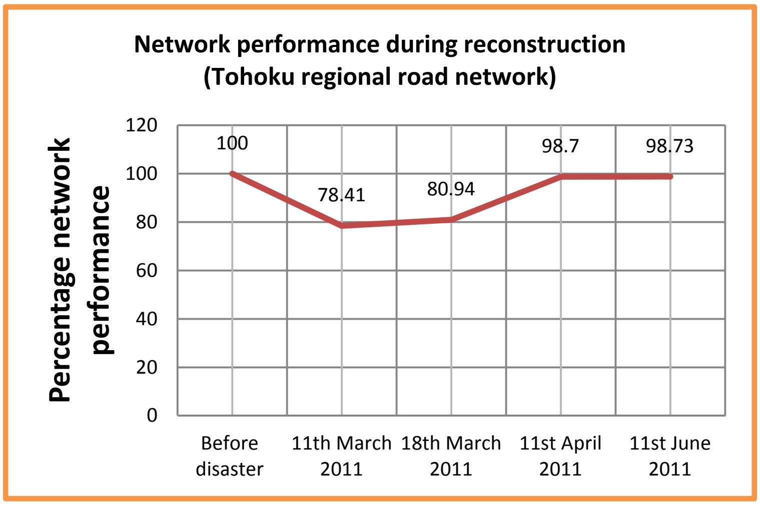


Figure 6.14: Network performance during reconstruction period, Japan

the closed links at any time. Figure 6.14 shows the situation of network performance index on different time of reconstruction period. The network performance was reduced by 21.59% immediately after earthquake and Tsunami in whole Tohoku region. 2.53 % was recovered within one week and 20.29% was recovered after one months. In this way this methodology can use to find out the network performance index at any time.

Discussion:

In our analysis, we consider only closure condition, the closure of link could be very small landslide which can be removed within few days or link can be closed by collapse of bridge which can take long time to recover. From our result from information of closure immediately after disaster (Figure 6.13 and Appendix: F) and information of closure after one week of disaster (Figure 6.15 and Appendix: H) we conclude that there should be consideration of the level of hazard or recovery time.

From the adoption of critical population which is to treat low populated area equally, findings are very interesting. Basically, identification of critical population can be done in two ways; the first one is decided by political leaders arbitrarily by some agreement between politicians. The other way is scientifically, which we applied here through sensitivity analysis. Figure 6.16 and Appendix I shows the links with priority number and without considering the critical distance and population. To compare the result with adoption of critical distance and population (figure 6.13) ,for example the link which connect to low populated (10890) town Rokkasho-mura (Appendix: A) through Aomori is prioritized as 22nd position in case without consideration of critical population (Figure 6.16 and Appendix I) whereas after consideration of critical population the same link prioritize as 18th position, therefore we can say the adoption of critical population is effective and justifies to the low populated area. In case of distance, the path below the 15 km (critical distance) range is very less so in the large area analysis the critical distance does not affected in this Tohoku region case very much.

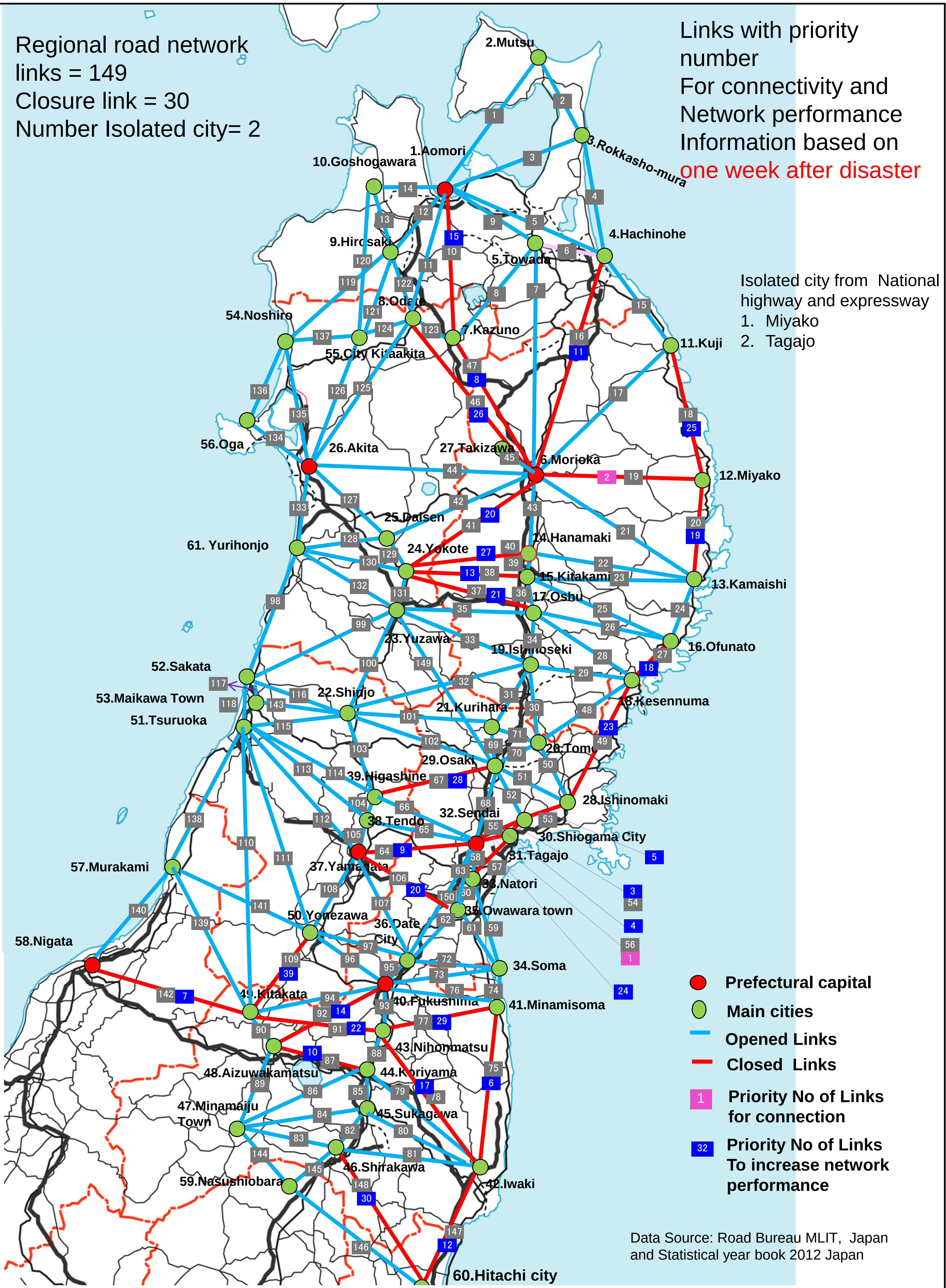


Figure 6.15: Map with final priority number of links (Analysis based on 1 weak after disaster) Tohoku Region, Japan

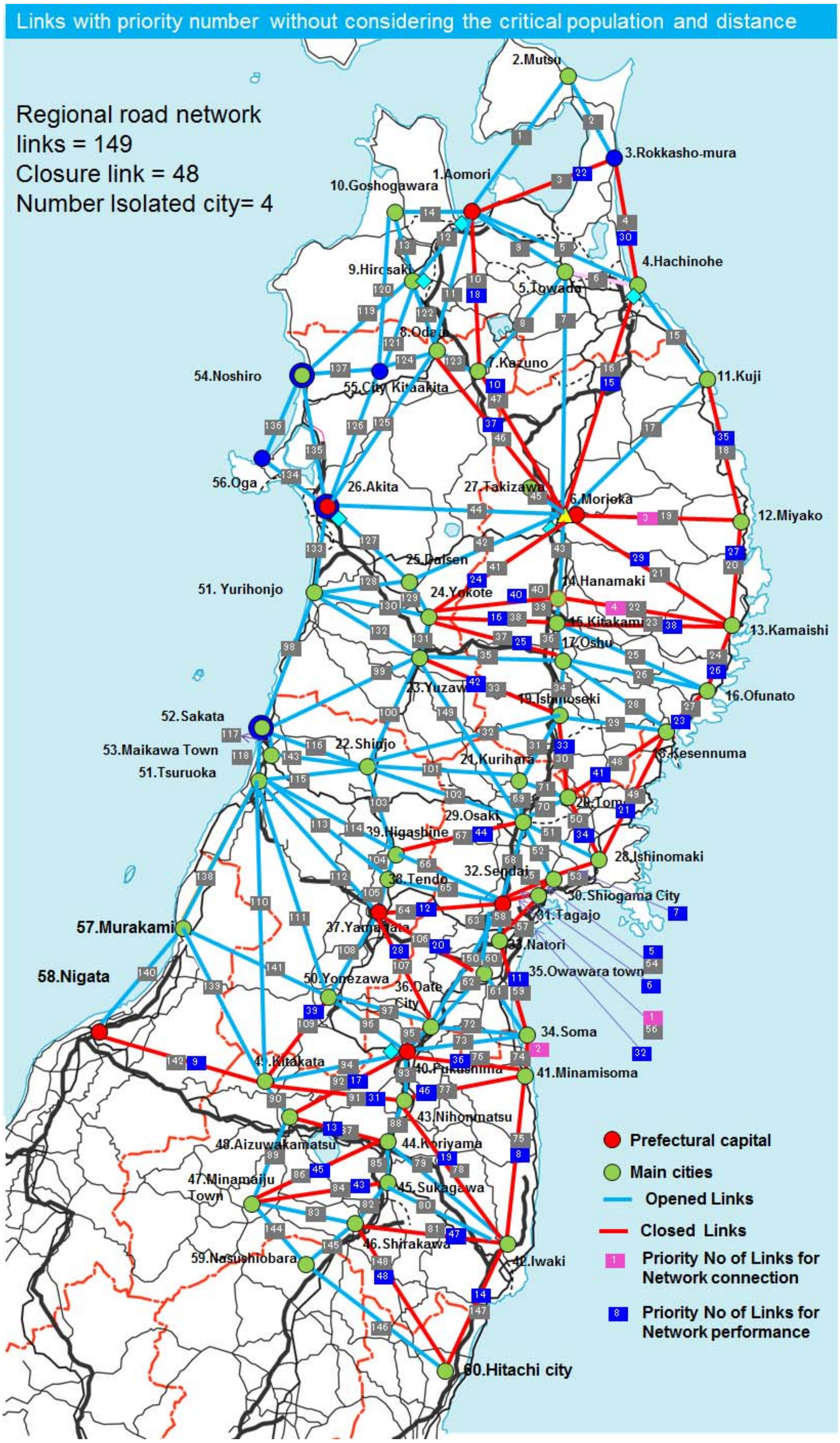


Figure 6.16: Links with priority number without considering the critical population and critical distance (Tohoku Region Japan)

6.2. Nepal's case study

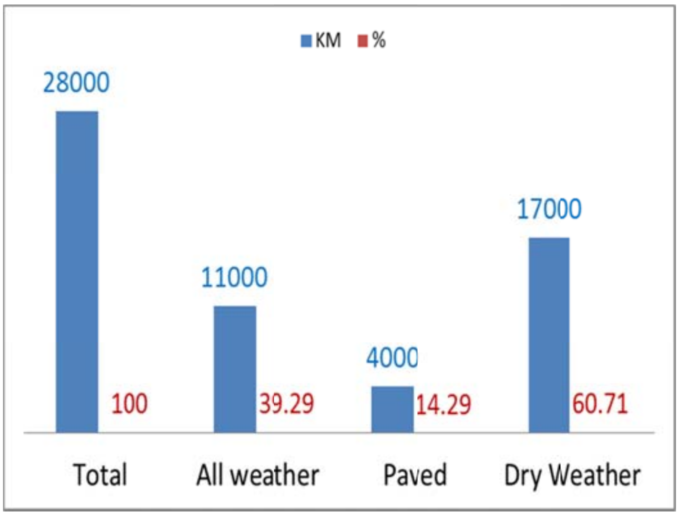
Nepal is a mountainous, land locked country in South Asia surrounded by India in East, South and west and by China in North. Condition of transport infrastructure is insufficient and poor. Total area of Nepal is 147,181 sq. km. Most of the rural road network sections in Nepal are closed in rainy season due to flooding in river, soil erosion in mountainous area, earthen condition of pavement and unavailability of bridge.

Figure 6.17: Nepal in Asia

Figure 6.18: District map of Nepal with study district

6.2.1. Nepal's District road network: Road network closure in rainy season

Out of 28000 km of road network paved road is only 4000 km and 17,000 km i.e. 60% of the road network is not functional in rainy season(Figure 6.19). People who are living in remote village have to walk more than one day. Government should upgrade the road condition "Dry weathered road" to "all weathered road" but it is not possible to upgrade all network at the same time due to budget constraints and other factors. Therefore, prioritization of road network link is necessary. A district transport master plan guideline (DoLIDAR 2010) proposed a scoring system for the prioritization of the road network mainly based on cost efficiency . Table 6.1 shows the different parameter and their score. Existing methodology mainly focus on the cost benefit analysis however a connectivity and accessibility problem creates severe impact in the rainy season. Our proposed methodology evaluates the road network links which can provide better accessibility and are prioritize at the top.



S.N.	Parameter	Scoring Unit	Score
I	Population per unit Cost	Population/investment Cost in 100000	55
ii	Cultivated Land	Cultivated Land/km	15
iii	Population × Walking hour	Population × Walking hour /km	20
iv	Total Population of poor, *Dalits* and marginalized *Janjatis*.	Population /km	10

The study place has been selected in Syangja district among 75 districts in Nepal, lies on 230 km west of Kathmandu and 30 K.M west of Pokhara (A famous tourist city in Nepal). Total area of the district is 1164 sq km.

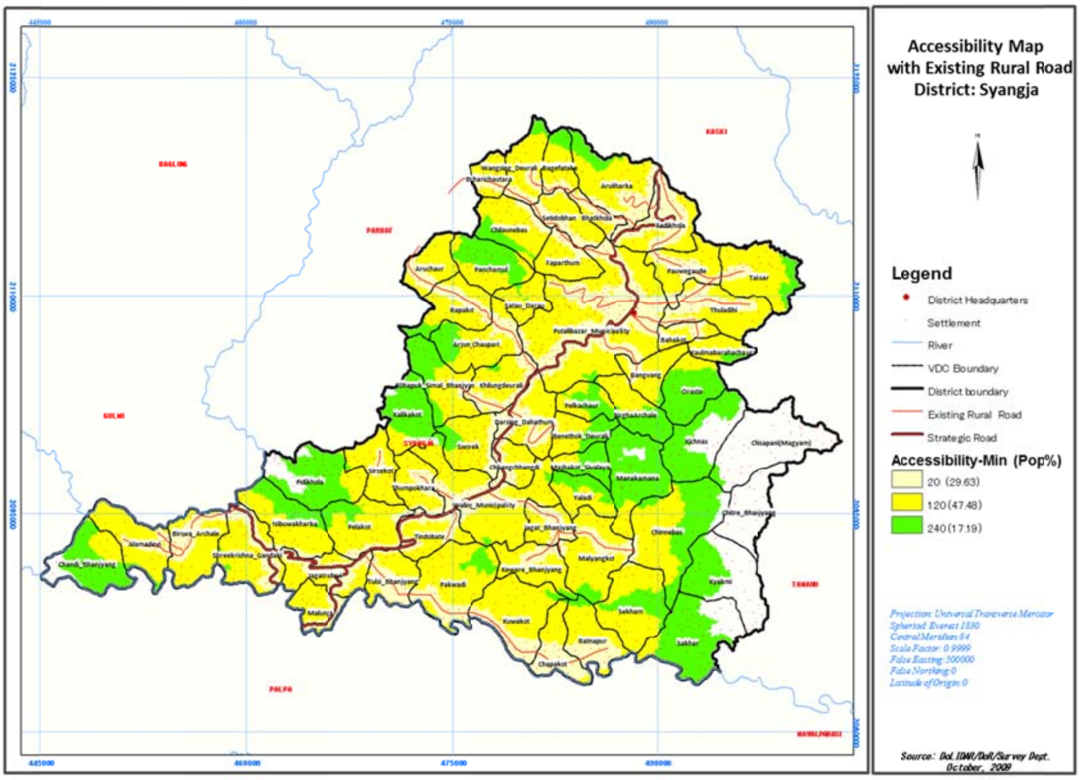
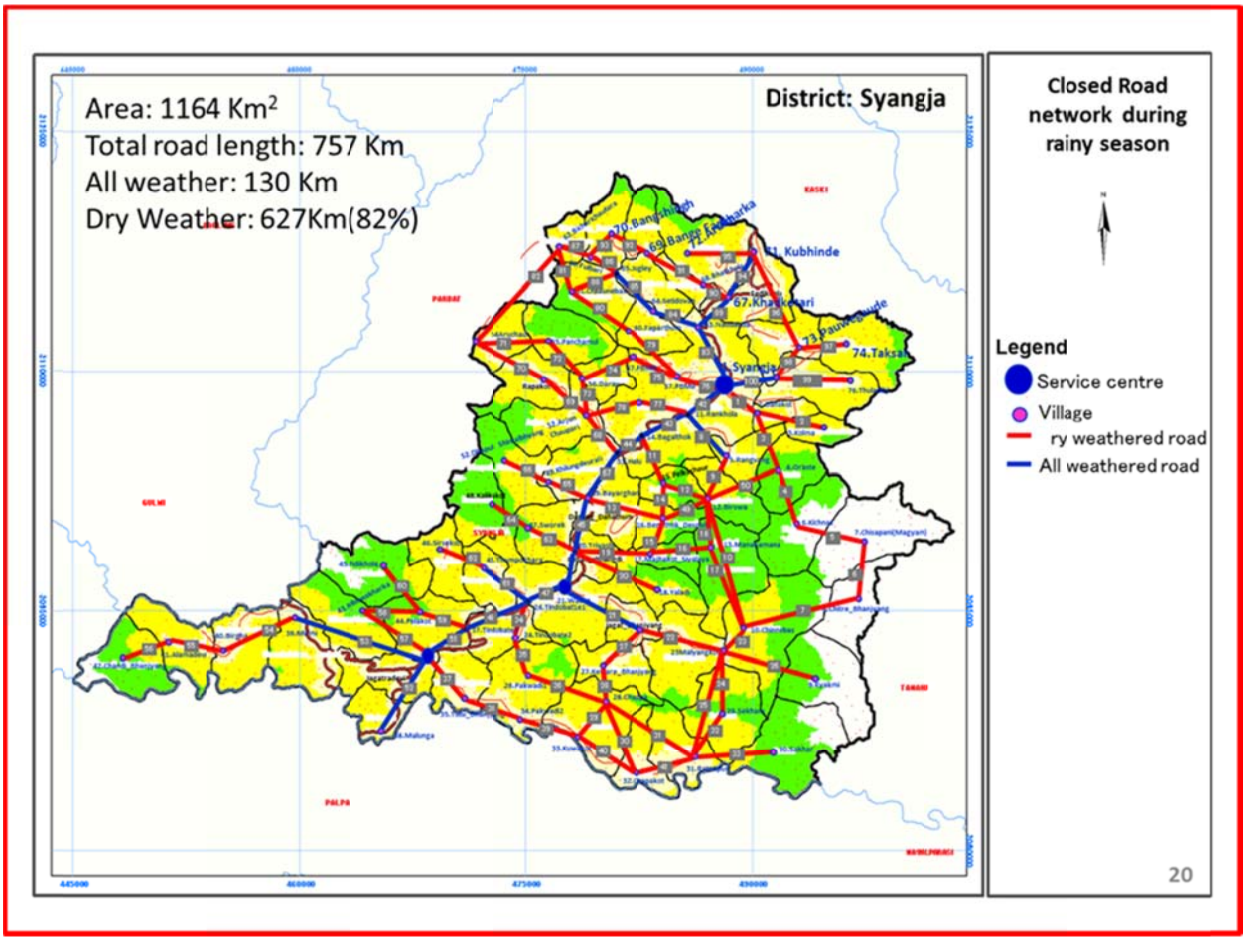


Figure 6.20: Government defined accessibility map, Syangja, Nepal

Figure 6.20 shows the government published accessibility map of the Syangja District. In this map the yellow part represents the road available within two hour of walking distance .Which means most part of the district road is accessible within 2 hour walking distance. But these roads are only available on dry season and most of the road network sections are closed during rainy season. As shown in Figure 6.21, blue link represents all weathered road and red link represents dry weather road. Out of 757 km, 627 km i.e 82% of road network are dry weathered and finally the road with yellow hatching on the map has no meaning in the rainy season. Some examples of 'Dry weathered road' and 'All weathered road' are shown in Figure 6.22.


Area: 1164 Km2
Total road length: 757 Km
All weather: 130 Km
Dry Weather: 627Km(82%)
District: Syangja
Closed Road network during rainy season
Legend
Service centre
Village
ry weathered road
All weathered road
20

Due to budget constraint it is not possible to upgrade the road network from 'Dry weathered' to 'All weathered' all at a time. There is a necessity of scientific methodology which can compare all road network sections and prioritize them. The proposed network evaluation methodology from the accessibility and network closure vulnerability approach; is also suitable to select and prioritize for this road network closure on rainy season.

We have applied the same methodology which we proposed in the Chapter 5 to prepare the priority list of links for upgrading projects from 'Dry Weathered' to 'All Weathered road'. Appendix J presents the road network information of Syangja District Nepal.

6.2.2. Sensitivity Analysis: Identification of critical distance and critical Population

As in the Case of Tohoku region, Japan we have decided the critical value of population and distance by sensitivity analysis Figure 6.23 shows the sensitivity analysis for the distance in the case of Nepal. The tendency of network performance index vs critical distance curve at population zero dramatically changes from 10 km so we decide the critical distance is 10 km. As in the Figure 6.24 the network performance index vs critical distance curves in various population verifies the chosen value of critical distance.

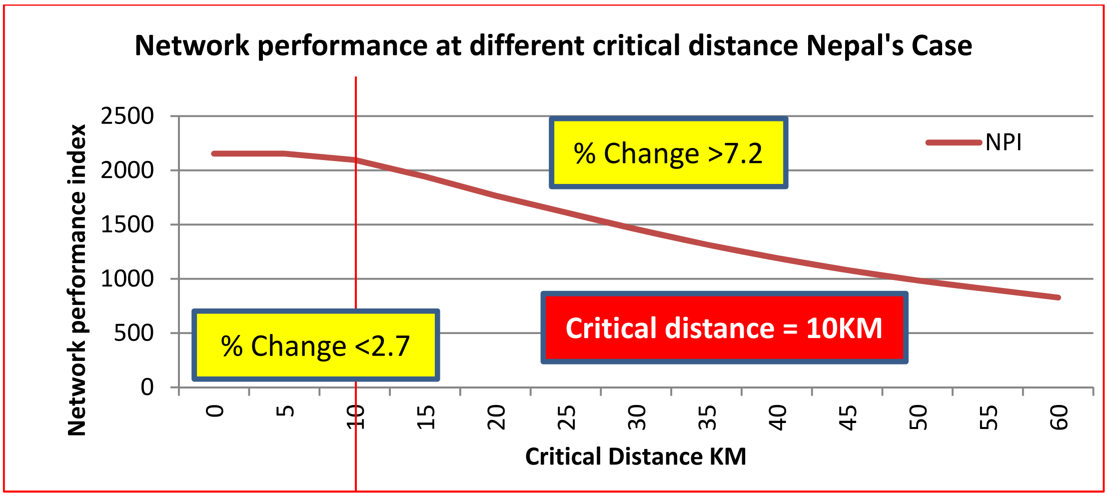


Figure 6.23: Critical distance vs Network performance index at critical population zero, Syangja, Nepal

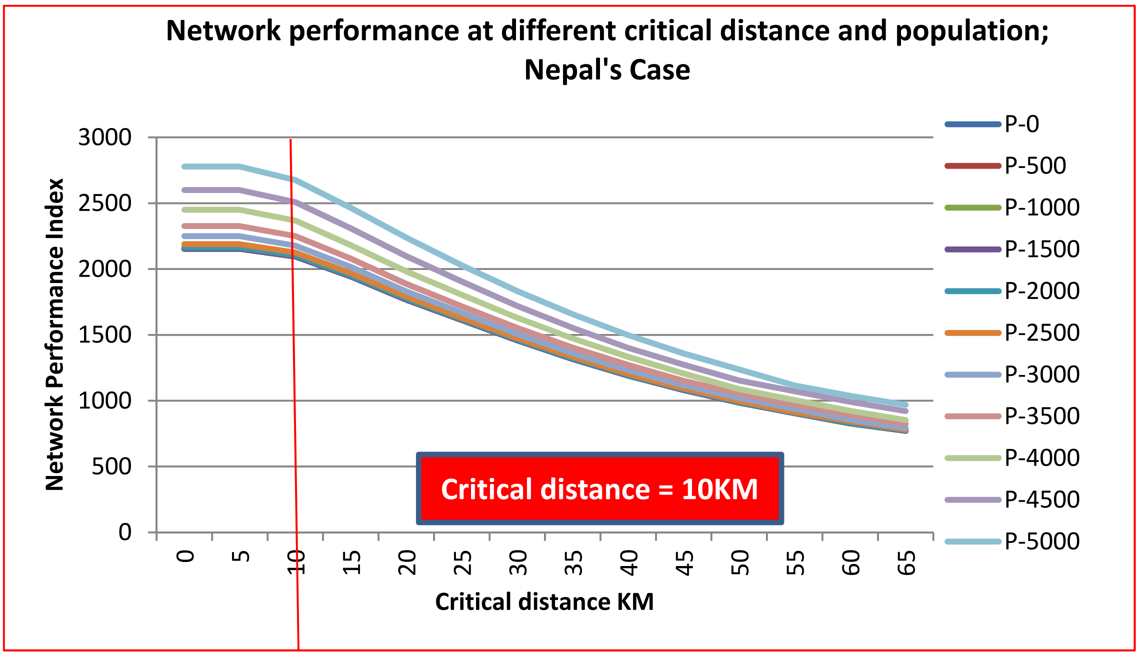


Figure 6.24: Critical distance and Network performance index at various critical populations, Syangja Nepal

Similarly for the critical population Figure 6.25 shows the tendency curve of critical population vs network performance index at zero critical distance.

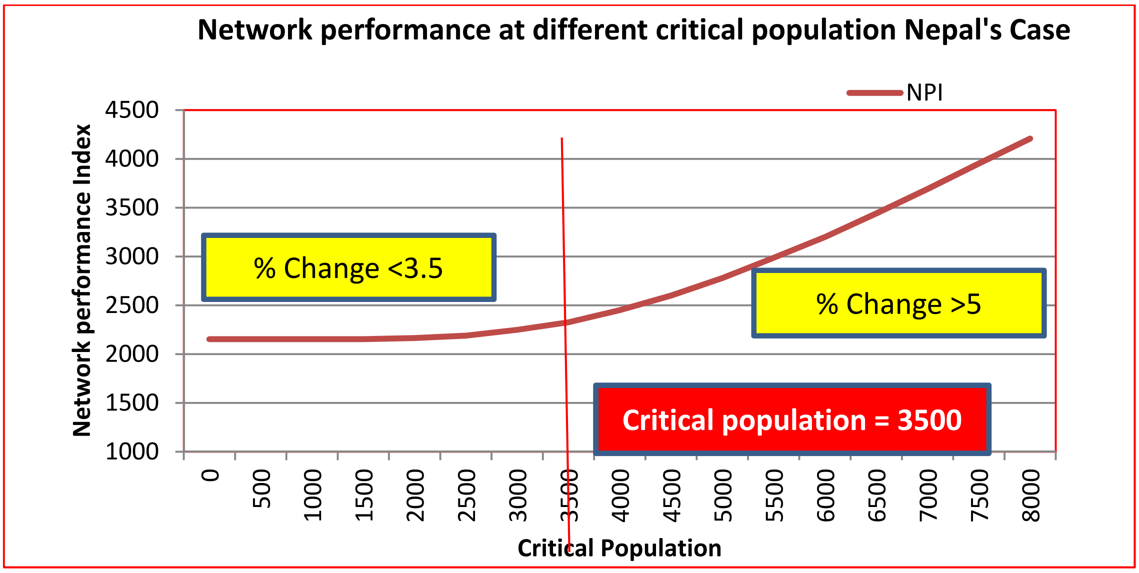


Figure 6.25: Critical population vs network performance index at zero critical distance, Syangja Nepal

The population 3500 where curve changes dramatically is decided as a critical population. Figure 6.26 shows the tendency of curves of critical population vs network performance index in different distance. The curve shows similar pattern on different critical distance hence decided value is OK.

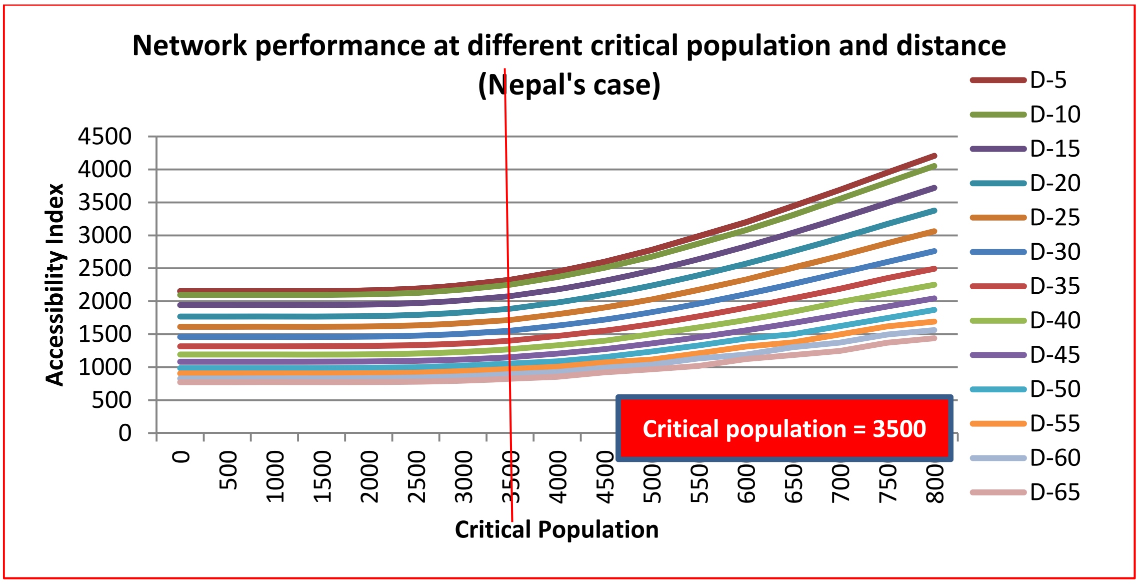


Figure 6.26: Critical population vs network performance index at various critical distances, Syangja Nepal

6.2.3. Prioritization of Dry Weathered links for the upgrading projects

With the decision of the critical distance and population the priority list of the dry weathered road section has been identified by following the step by step calculation processes proposed in Chapter 5. We adopted the detour ratio as 2 for this case because the case we choose is for the analysis in rural area of developing country, where all weathered road length is very low.

There are 55 villages isolated during rainy season in Syangja district. Figure 6.27 shows the important link for the network connection with the priority number and Figure 6.28 shows the important links for the network performance after recovering the isolation including important links for connection. The final result of priority list of links is presented in Appendix K.

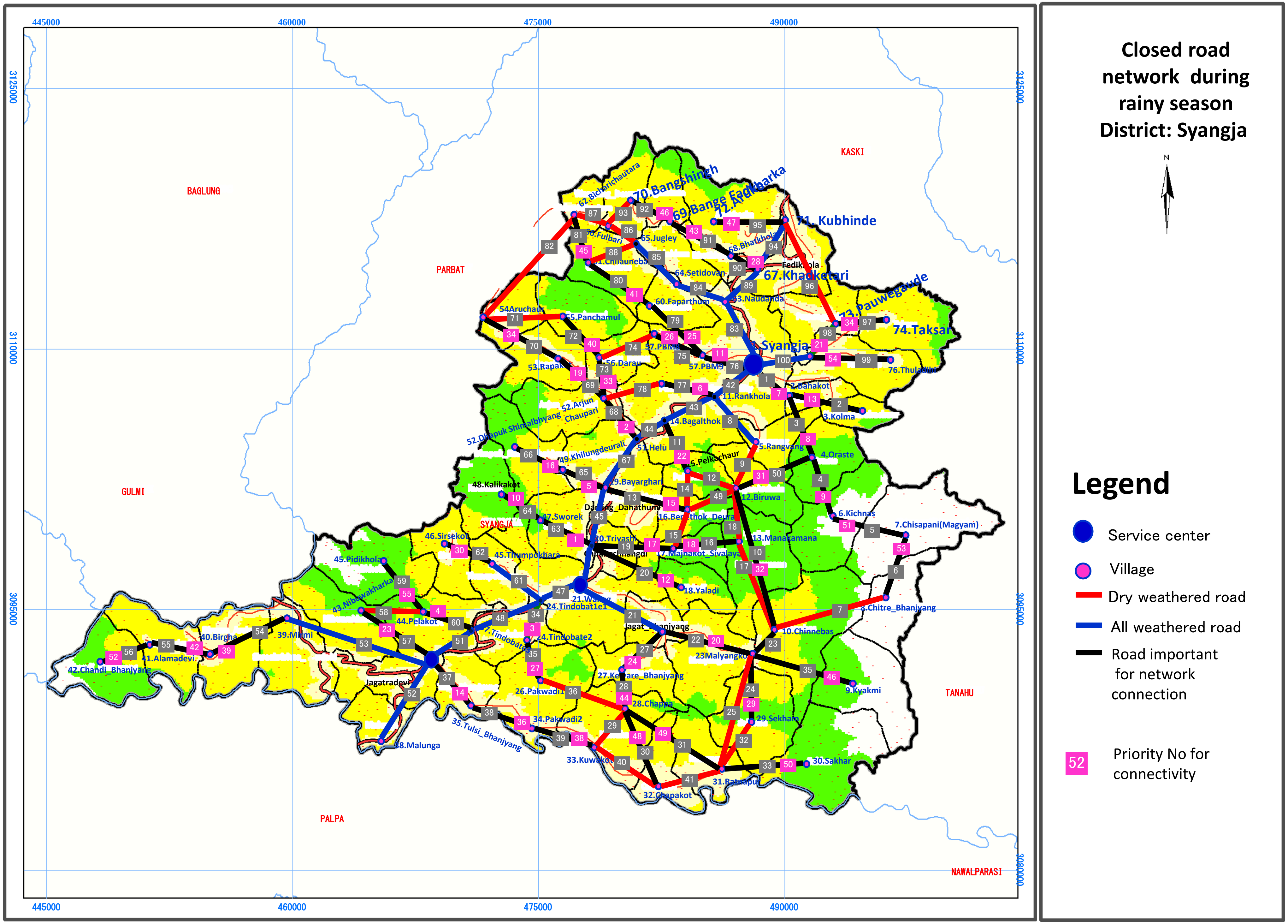


Figure 6.27: Dry weathered links with priority number for network connectivity, Syangja Nepal

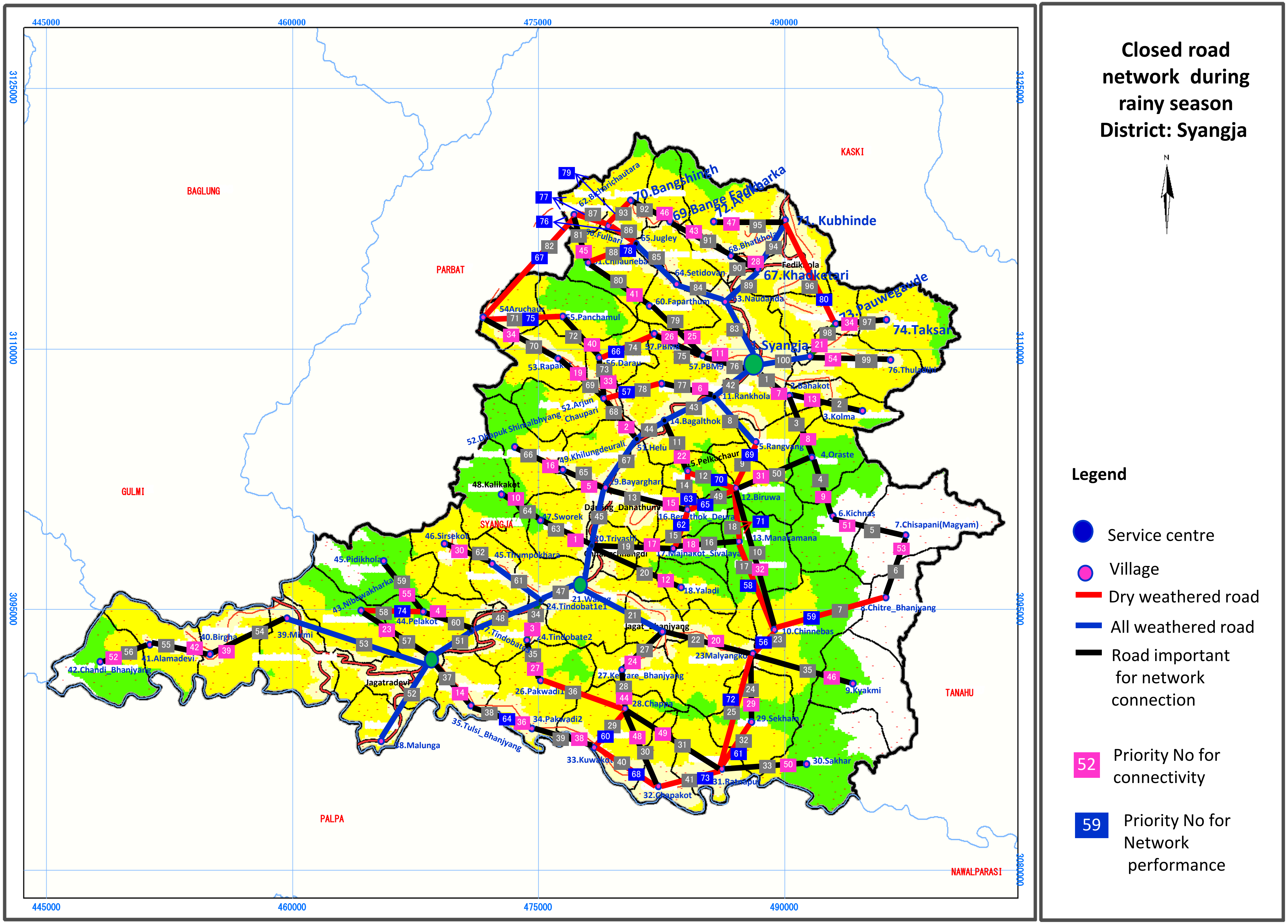


Figure 6.28: Dry weathered links with priority number for network connectivity and network performance , Syangja Nepal

Discussion:

In the case of Nepal, we have analyzed by both; i.e adoption of critical value (Population and Distance) and without adoption of critical value. Figure 6.28 and Appendix J shows the result of adoption of critical value and Figure 6.29 and Appendix: L shows the result without adopting the critical value. By comparing these two results we can clearly see the link(link no 76) which connects to PBM 9 from service center Syangja has low population (2000) and distance 9 km which changes the position from 23 (without adoption) to 11 (with adoption). Similarly, link which connects the village Kolma from Bahakot has population 2471 (less than critical value 3500) but distance 11 km which is greater than critical value (10 km) has shifted the position from 21(without adoption of critical population) to 13 (with adoption of critical population). Therefore, we conclude that for the local level analysis, the adoption of critical population and critical distance both are very much effective.

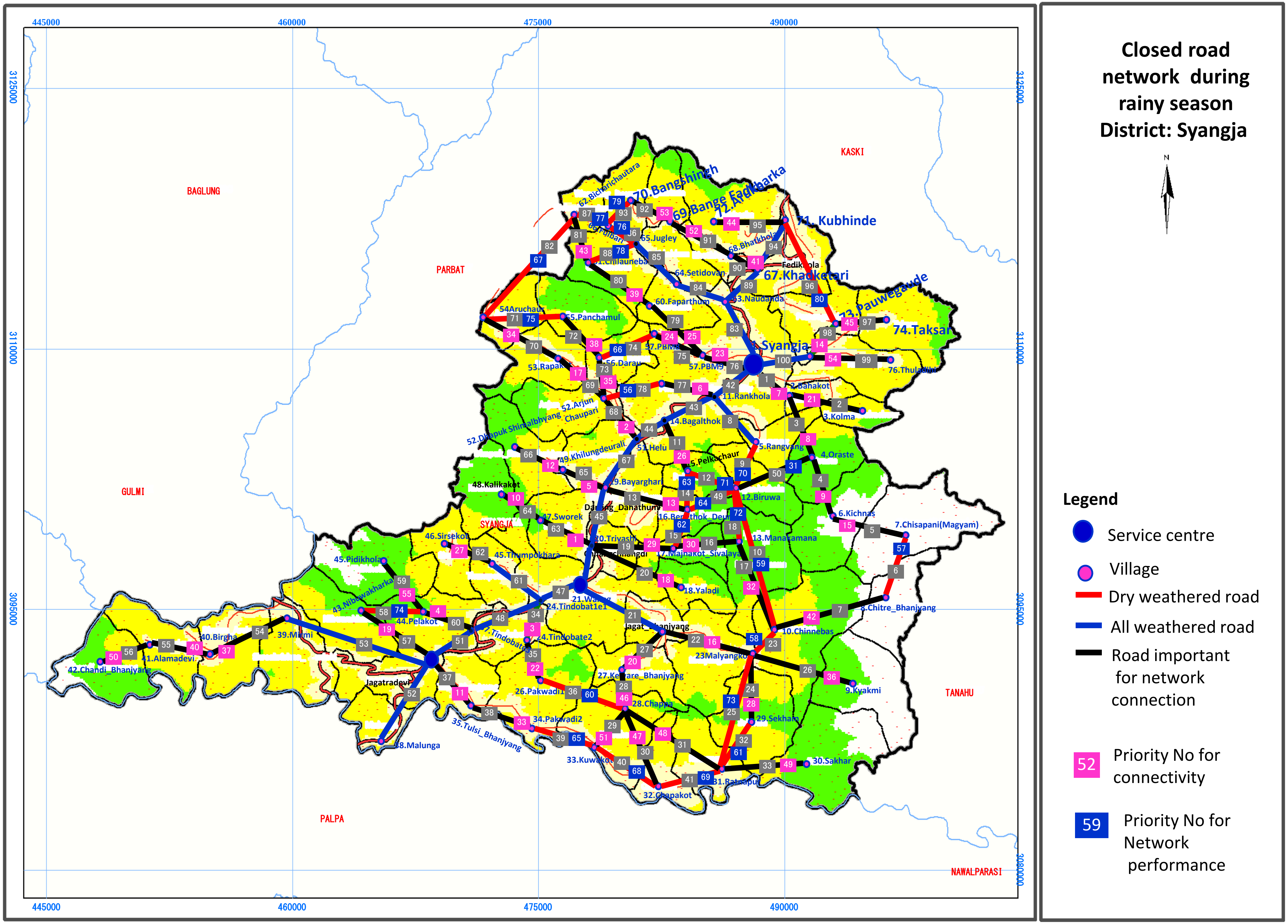


Figure 6.29: Links with priority number without considering the critical population and distance

7. Conclusion, Discussion and further Research

The motivation for the research presented in this thesis is to propose a methodology for the prioritization of road network links to improve or upgrading project under the multiple link closure events. In section 7.1 we briefly summarize our study.

7.1. Brief Summary

Access to the goods and services for the daily needs is primary requirement for every people even in any kinds of emergency situation. Road network becomes unreliable due to natural disaster, or extreme weather condition. Closure on the road network creates a state of isolation or loss of accessibility of village, city and town. Severity and weakness in the network are differing from location to location. Identification of weakest location and critical links in a network and prioritize them for the improvement projects is the purpose of the evaluation methodology. We reviewed the contemporary research on reliability of road network.

Although, numerous studies have been done on the reliability of road network to find critical links and prioritize them for the improvement, there is a lack of practical evaluation methodology. However, contemporary researches yield the very important concepts and ideas for the future research. Conceptual study gives various relevant concepts of reliability of road network and classification of reliability. Mathematical theoretical methodology evaluates the reliability by mathematical model. Existing evaluation methodologies evaluate the performance under uncertain and emergency situation. Descriptive type study explains about the problems on the practical field and problems faced by the practitioner. Application study is the case study which has been applied in the specific area. Ways to improve reliability demonstrated the policy issues for the improvement of network reliability.

We have analyzed the existing practical methodologies under various multi-dimensional criteria, such as evaluation index, data requirement, computation time, probability of adverse events, theoretical importance, socioeconomic impact, one link failure and area wise impact and isolation of area with the positive and lacking perspective. We have found that the existing methodologies measure the link criticality indices considering the socioeconomic impact and other factor of the link disruption. However, the main weakness of the existing evaluation methodologies is unable to address multiple link failure condition .Also consideration of closure events in the respective links without separation of possible close links and fine links. Some of them have treated every link equally. While in the emergency situation all links don't have equal possibility of closure. Other weakness is that some of the methodologies use the parameter like traffic volume and travel times which are uncertain at the emergency situation.

We have done the series of computational experiment in the real practical problem by using the existing evaluation methodology and proposed model.

We develop the network evaluation methodology based on accessibility and network closure vulnerability approach. A Network Performance Index (NPI) was derived in order to quantify the potential impact to the network due to closure of link and upgrading of closed links. Cumulative effects of link improvement were observed for the comparison among the links.

Proposed evaluation methodology prioritizes the possible closed road network link in two stages. First stage identifies the important link for the network connection. Second stage identifies the important links to increase the network performance. The method of sensitivity analysis is also adopted to identify the critical population and critical distance. Critical population and critical distance is taken as a threshold value in the methodology which treated the less populated area and area within the some mobility range equally. Redundancy evaluation of the alternative link is adopted whether it is in acceptable range or not.

We have applied the proposed evaluation methodology in the regional road network in the Tohoku region of Japan, where numerous road network links were closed due to Great East Japan Earthquake occurred in 11th March, 2011 and district road network in

Syangja district of Nepal, where 80% of the rural road network are closed during rainy season. By using this methodology we prepared the priority list of the road network link for the improvement or upgrading projects.

7.2. Discussion

This research proposed the road network evaluation methodology under multiple road network closure events. Methodology compares the network performance of a possible closed links when upgraded and prepares the priority list of the links for the efficient allocation of resources. Here is some discussion, application and analysis.

This thesis proposed a road network evaluation methodology for the case of multiple link closure. From the multidirectional analysis and computational experiment of the existing evaluation methodology we found they cannot solve the problem of multiple link failure.

Proposed evaluation methodology identifies the important links and prioritizes them for the connection of isolated node (village, city, and town) at top position. An accessibility index of isolated node is calculated due to upgrading of particular closed link. More than isolated node could be benefited with upgrading of one link so methodology calculates the total accessibility index, we called Network performance index due to upgrading of particular link. Important link is selected with highest network performance index. After achievement of connectivity other remaining closed links are prioritize. We first proposed the strategy which focused on connectivity.

1. This research employed the acceptable range of alternative available route by evaluating “Redundancy” through detour ratio in the whole calculation process. Redundant link is very important for the connectivity of isolated node however it should be acceptable, we proposed different value for the developed country and developing country.
2. In our model highly populated and nearest city/town/village from the city service center can get priority. This model could be justifiable if one consider the economic perspective. But from the social responsibility or policy maker side, it could not be suitable. Therefore we adopted the sensitivity analysis to

find out the critical value of the population and distance. The city/village/town which lies under this critical value is treated as equivalent.

3. The proposed methodology can be used by any level of road network i.e. the road network under the responsibility of the each level of government authority. Or it can be used in specific selected area.

7.3. Further Research

Reliability of transportation network is an emerging field of research so there are many opportunity for the further research. We reviewed in the chapter 2; showing the importance of reliability of transportation network. In this section we present the issues on the road network closure for further research.

We applied this methodology to identify the network performance during reconstruction period in Tohoku region of japan. Many road sections were opened within one week. There is a level of hazard in each link; further research may consider the level of hazard in the link or possible time taken to reconstruct links.

For the disaster preparedness activities, every links do not have same probability of damage from different disaster events. So probability of damage could be incorporated in the further research.

Considering the degree of weakness against disaster in terms of geotechnical condition, strength of structure, construction technique used etc. could be the way to differentiate the level of disruption and associated recovery time in the future analysis.

Congestion and capacity problem in the survived route could be another topic for the future research.

We applied the methodology for upgrading project from 'Dry weathered' to 'All weathered road' in Nepal. Here, we consider the parameter only population and distance between the village and service center. Upgrading the road network project is directly related to the economic development of the country. By considering the economic growth potential of the village or Gross regional product (GRP) the evaluation methodology could be even elaborated.

References

Asakura, Y. (1999). "Evaluation Of Network Reliability Using Stochastic User Equilibrium." Journal of Advanced Transportation **33**(2): 147-158.

Bell, M. G. H. (2000). "A game theory approach to measuring the performance reliability of transport networks." Transportation Research Part B **34**(533-545).

Bell, M. G. H. and Y. Iida, Eds. (1997). Transportation Network Analysis John Wiley & Sons

Berdica, K. (2002). "An introduction to road vulnerability: what has been done, is done and should be done." Transport Policy **9**(2): 117-127.

Chang, S. E. and N. Nojima (2001). "Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective." Transportation Research Part A: Policy and Practice **35**(6): 475-494.

Chen, A., C. Yang, et al. (2007). "Network-based Accessibility Measures for Vulnerability Analysis of Degradable Transportation Networks." Networks and Spatial Economics **7**(3): 241-256.

Chen, A., H. Yang, et al. (1999). "A Capacity Related Reliability For Transportation Networks." Journal of Advanced Transportarion **33**(2): 183-200.

Consortium, C. U. E. (1996). Earthquake Vulnerability of Transporatation Systems In the Central Unites States U.S. Department of Transportation Research and Special Programs Administration Office of Emergency Transportation, http://www.cusec.org/publications/planning/dotmonograph.pdf(accessed 10/27/2011).

Dalziell, E. and A. Nicholson (2001). "Risk and Impact of Natural Hazards on a Road Network " Journal of Transportation Engineering **March/April 2001**: 159-166.

DoLIDAR (2010). Interim Guideline for District Transport Master Plan(DTMP) Preparation D. o. L. I. D. a. A. Roads.

FHWA (2008). Highways of the Future—A Strategic Plan for Highway Infrastructure Research and Development 6300 Georgetown Pike McLean, VA 22101-2296, US Department of Transportation **PUBLICATION NO. FHWA-HRT-08-068**.

Garrison, W. L. (1960). "Connectivity of interstate Highway System." Papers and Procedings of the Regional Science Association **6**.

Hansen, W. G. (1959). "How Accessibility Shapes Land Use." Journal of the American Institute of Planners **25**(2): 73-76.

Hou, P. and Y. Hsu (2005). "Finding Dominant Links of Emergency Network with Respect to Earthquake Disaster." Journal of the Eastern Asia Society for Transportation Studies **6**(77): 77-90.

Husdal, J. (2004). Reliability and Vulnerability Versus Costs and Benefits. Second International Symposium on Transportation Network Reliability. Christchurch and Queenstown, NZ, 20-24 August 2004, http://www.husdal.com/2004/08/25/reliability-and-vulnerability-versus-costs-and-benefits/ (accessed 4/2/2012).

Iida, Y. (1999). "Basic Concepts And Future Directions Of Road network reliability analysis." Journal of Advanced Transportarion **33**(2): 125-134.

Iida, Y., F. Kurauchi, et al. (2000). "Traffic Management System Against Major Earthquake " International Association of Traffic Safety Science **24**(2): 6-17.

Jenelius, E., T. Petersen, et al. (2006). "Importance and exposure in road network vulnerability analysis." Transportation Research Part A: Policy and Practice **40**(7): 537-560.

Kawasaki, S. (2011). Issues and Lessons Learned from Great earthquake in Japan. XXIVth World Road Congress Mexico http://www.road.or.jp/english/news/pdf/111003.pdf accessed 10/23/2011.

Krik, A. and M. Chen (2007). Route Disruption Analysis U. o. K. Kentucky Transportation Center Lexington, Kentucky University of Kentucky, Collage of Engineering

Litman, T. (2012). "Evaluating Accessibility for Transportation Planning." VIctoria Transport Policy Institute **http://www.vtpi.org/access.pdf accessed on 2012-7-16**.

MLIT (2011a). Disaster measurement manual based on improvement between major cities 主要都市・拠点間等の防災機能向上に関する 計測マニュアル（暫定案） MInister of Land Infrastructure Transport and Tourism,Japan http://www.mlit.go.jp/road/ir/ir-hyouka/pdf/toshi_manual.pdf (accessed 11/16/2011).

MLIT (2011b). Enhancement of the entire network for disaster prevention measrement manual ネットワーク全体の防災機能向上に関する 計測マニュアル（暫定案） Road Beuro, MLIT, Japan http://www.mlit.go.jp/road/ir/ir-hyouka/pdf/nw_manual.pdf (accessed 11/16/2011).

Nicholson, A. (2003). "Transport Network Reliability Measurement and Analysis " TRANSPORTES **XI**: 49-62.

Nicholson, A. and Z. P. Du (1997). "Degradable transportation systems An integrated equilibrium model." transport Research B **31**(3): 209-223.

Nicholson, A., J.-D. Schmocker, et al. (2003). "Assessing Transport Reliability: Malevolence and User Knowledge." The Network Reliability of Transport ,Proceedings of the 1st International Symposium on Transportation Network Reliability(INSTR), Elsevier Science Ltd.: 1-22.

OECD (2010). Improving Reliability on Surface Transport Network, Transport Research Center

Peeta, S., F. Sibel Salman, et al. (2010). "Pre-disaster investment decisions for strengthening a highway network." Computers & Operations Research **37**(10): 1708-1719.

Pokharel, R. and H. Ieda (2012). "Reliability and Vulnerability of Road Network: A Research Review from Practicability Perspective." Procedings of Infrastructure planning, Japan Society of Civil Engineers **45**.

Ramirez, J., S. Peeta, et al. (2005). Emergency Earthquake Routes; Part I, Criteria for Selection of Primary Routes. I. D. o. T. a. P. University. West

Lafayette, Indiana, 2005. doi: 10.5703/1288284313203. **Publication FHWA/IN/JTRP-2003/22.**

Reconstruction (2011). Basic guidelines for reconstruction R. H. Japan, The reconstruction headquarters in response to the great east Japan earthquake http://www.reconstruction.go.jp/topics/0810basic_guidelines_reconstruction_20110729.pdf (accessed 2011-12-31)

Sakakibara, H., Y. Kajitani, et al. (2004). "Road Network Robustness for Avoiding Functional Isolation in Disasters." Journal of Transportation Engineering **130**(5): 560-567.

Saltelli, A., K. Chan, et al., Eds. (2008). Sensitivity Analysis, Wiley.

Sánchez-Silva, M., M. Daniels, et al. (2005). "A transport network reliability model for the efficient assignment of resources." Transportation Research Part B: Methodological **39**(1): 47-63.

Scott, D. M., D. C. Novak, et al. (2006). "Network Robustness Index: A new method for identifying critical links and evaluating the performance of transportation networks." Journal of Transport Geography **14**(3): 215-227.

Shizuoka, P. (2010). Tokai Earthquake Preparedness in Shizuoka Prefecture , Japan Shizuoka Prefecture http://www.equakes.pref.shizuoka.jp/center/guidebook/pdf/earthquakepreparedness_in_shizuoka 2010.pdf (accessed 11/25/2011).

Snelder, M. (2010). Designing the Robust Road Networks;A general design method applied to the Netherlands TRAIL Research School Delft University of Technology **PhD Thesis**

Sohn, J. (2006). "Evaluating the significance of highway network links under the flood damage: An accessibility approach." Transportation Research Part A: Policy and Practice **40**(6): 491-506.

Susilawati and M. Taylor (2008). "An accessibility approach in assessing regional road network vulnerebility." Australian Transport Research Forum **31st**

Taylor, M. A. P., S. V. C. Sekhar, et al. (2006). "Application of Accessibility Based Methods for Vulnerability Analysis of Strategic Road Networks." Networks and Spatial Economics **6**(3-4): 267-291.

Upadhyaya, B. (2009). "Rural Infrastructure Development & Prospect and Status of Consultancy Business in Nepal." Procedings of International Conference on 'Making Globalization a Role of Consultant' **http://scaef.org.np/conference/conference/pdf/Session-/4.%20Business%20Paper-Bhim.pdf accessed on 09-06-2012**.

Wakabayashi, H. and Y. Iida (1992). "Upper and Lower Bounds of Terminal Reliability of Road Networks:An Efficient Method With Boolean Algebra." Journal of Natural Disaster Science **14**(1): 29-44.

Yin, Y. and H. Ieda (2001). "Assessing Travel Time Reliability of Road Networks Considering Day to Day Travel Variations " Journal of Eastern Asia Society for Transportation Studies **4**(2): 125-137.

Appendix A: Information of National Highway and Expressway network in different time after the 3/11's Great East Japan Earthquake

Link NO	From					TO					can pass：○、cannot pass：×					
	City/Town/ Village in Japanese	City/Town/ Village in English	Node No	Prefecture	Population	City/Town/ Village in Japanese	City/Town/ Village in English	Node No	Prefecture	Population	Distance (KM)	Travel time (Hour)	information on March 12 2011	information on March 18 2011	information on April 11 2011	information on June 11 2011
1	青森市	Aomori	1	Aomori	2,99,429	むつ市	Mutsu	2	Aomori	61,053	100.9	2.9	○	○	○	○
2	むつ市	Mutsu	2	Aomori	61,053	六ヶ所村	Rokkasho-mura	3	Aomori	10,890	53.0	1.5	○	○	○	○
3	青森市	Aomori	1	Aomori	2,99,429	六ヶ所村	Rokkasho-mura	3	Aomori	10,890	85.1	2.5	×	○	○	○
4	六ヶ所村	Rokkasho-mura	3	Aomori	10,890	八戸市	Hachinohe	4	Aomori	2,37,473	59.5	1.6	×	○	○	○
5	青森市	Aomori	1	Aomori	2,99,429	八戸市	Hachinohe	4	Aomori	2,37,473	94.7	2.6	○	○	○	○
6	八戸市	Hachinohe	4	Aomori	2,37,473	十和田市	Towada	5	Aomori	66,123	33.2	0.9	○	○	○	○
7	十和田市	Towada	5	Aomori	66,123	盛岡市	Morioka	6	Iewate	2,98,572	160.6	3.1	○	○	○	○
8	十和田市	Towada	5	Aomori	66,123	鹿角市	Kazuno	7	Akita	34,479	83.2	2.4	○	○	○	○
9	青森市	Aomori	1	Aomori	2,99,429	十和田市	Towada	5	Aomori	66,123	61.1	1.7	○	○	○	○
10	青森市	Aomori	1	Aomori	2,99,429	鹿角市	Kazuno	7	Akita	34,479	93.3	1.7	×	×	○	○
11	青森市	Aomori	1	Aomori	2,99,429	大館市	Odate	8	Akita	78,951	81.7	1.7	○	○	○	○
12	青森市	Aomori	1	Aomori	2,99,429	弘前市	Hirosaki	9	Aomori	1,83,534	47.2	1.0	○	○	○	○
13	弘前市	Hirosaki	9	Aomori	1,83,534	五所川原市	Goshogawara	10	Aomori	58,423	26.8	0.8	○	○	○	○
14	青森市	Aomori	1	Aomori	2,99,429	五所川原市	Goshogawara	10	Aomori	58,423	41.1	0.8	○	○	○	○
15	久慈市	Kuji	11	Iwate	36,875	八戸市	Hachinohe	4	Aomori	2,37,473	54.2	1.5	○	○	○	○
16	盛岡市	Morioka	6	Iwate	2,98,572	八戸市	Hachinohe	4	Aomori	2,37,473	136.1	2.6	×	×	○	○
17	盛岡市	Morioka	6	Iwate	2,98,572	久慈市	Kuji	11	Iewate	36,875	151.0	3.2	○	○	○	○
18	久慈市	Kuji	11	Iwate	36,875	宮古市	Miyako	12	Iewate	59,442	101.1	2.8	×	×	○	○
19	盛岡市	Morioka	6	Iwate	2,98,572	宮古市	Miyako	12	Iewate	59,442	105.6	3.0	×	×	○	○
20	宮古市	Miyako	12	Iwate	59,442	釜石市	Kamaishi	13	Iewate	39,578	56.0	1.4	×	×	×	○
21	盛岡市	Morioka	6	Iwate	2,98,572	釜石市	Kamaishi	13	Iewate	39,578	104.0	2.8	×	○	○	○
22	釜石市	Kamaishi	13	Iwate	39,578	花巻市	Hanamaki	14	Iewate	1,01,451	83.0	2.2	×	○	○	○
23	釜石市	Kamaishi	13	Iwate	39,578	北上市	Kitakami	15	Iewate	93,147	86.2	2.2	×	○	○	○
24	釜石市	Kamaishi	13	Iwate	39,578	大船渡市	Ofunato	16	Iewate	40,738	40.4	1.0	×	○	○	○
25	大船渡市	Ofunato	16	Iwate	40,738	北上市	Kitakami	15	Iewate	93,147	81.1	2.3	○	○	○	○
26	大船渡市	Ofunato	16	Iwate	40,738	奥州市	Oshu	17	Iewate	1,24,756	66.9	1.9	○	○	○	○
27	大船渡市	Ofunato	16	Iwate	40,738	気仙沼市	Kesennuma	18	Miyagi	73,494	35.2	1.0	×	×	×	×
28	気仙沼市	Kesennuma	18	Miyagi	73,494	奥州市	Oshu	17	Iewate	1,24,756	60.5	1.7	○	○	○	○
29	気仙沼市	Kesennuma	18	Miyagi	73,494	一関市	Ichinoseki	19	Iewate	1,18,602	46.6	1.3	○	○	○	○
30	一関市	Ichinoseki	19	Iwate	1,18,602	登米市	Tome	20	Miyagi	83,973	38.0	1.1	×	○	○	○
31	一関市	Ichinoseki	19	Iwate	1,18,602	栗原市	Kurihara	21	Miyagi	74,938	35.5	0.7	○	○	○	○
32	一関市	Ichinoseki	19	Iwate	1,18,602	新庄市	Shinjo	22	Yamagata	38,856	128.0	2.9	○	○	○	○
33	一関市	Ichinoseki	19	Iwate	1,18,602	湯沢市	Yuzawa	23	Akita	50,863	110.2	1.9	×	○	○	○
34	一関市	Ichinoseki	19	Iwate	1,18,602	奥州市	Oshu	17	Iewate	1,24,756	29.1	0.7	○	○	○	○
35	奥州市	Oshu	17	Iwate	1,24,756	湯沢市	Yuzawa	23	Akita	50,863	84.6	1.5	○	○	○	○
36	奥州市	Oshu	17	Iwate	1,24,756	北上市	Kitakami	15	Iewate	93,147	23.8	0.5	○	○	○	○
37	奥州市	Oshu	17	Iwate	1,24,756	横手市	Yokote	24	Akita	98,379	72.5	1.3	×	×	○	○
38	北上市	Kitakami	15	Iwate	93,147	横手市	Yokote	24	Akita	98,379	58.3	1.0	×	×	○	○
39	北上市	Kitakami	15	Iwate	93,147	花巻市	Hanamaki	14	Iewate	1,01,451	10.5	0.3	○	○	○	○
40	花巻市	Hanamaki	14	Iwate	1,01,451	横手市	Yokote	24	Akita	98,379	68.8	1.3	×	×	○	○
41	盛岡市	Morioka	6	Iwate	2,98,572	横手市	Yokote	24	Akita	98,379	115.8	2.1	×	×	○	○
42	盛岡市	Morioka	6	Iwate	2,98,572	大仙市	Daisen	25	Akita	88,299	86.2	2.5	○	○	○	○
43	盛岡市	Morioka	6	Iwate	2,98,572	花巻市	Hanamaki	14	Iewate	1,01,451	54.3	1.1	○	○	○	○
44	盛岡市	Morioka	6	Iwate	2,98,572	秋田市	Akita	26	Akita	3,23,363	181.1	3.3	○	○	○	○
45	盛岡市	Morioka	6	Iwate	2,98,572	滝沢村	Takizawa	27	Iewate	52,981	12.2	0.3	○	○	○	○
46	盛岡市	Morioka	6	Iwate	2,98,572	大館市	Odate	8	Akita	78,951	132.0	2.8	×	×	○	○
47	盛岡市	Morioka	6	Iwate	2,98,572	鹿角市	Kazuno	7	Akita	34,479	93.5	1.8	×	×	○	○
48	気仙沼市	Kesennuma	18	Miyagi	73,494	登米市	Tome	20	Miyagi	83,973	54.0	1.5	×	○	○	○

Data source: 1. Road information: Road Bureau MLIT, Japan
2. Population: Statistical year book 2012, Japan

Link NO	From					TO							can pass：○、cannot pass：×			
	City/Town/ Village in Japanese	City/Town/ Village in English	Node No	Prefecture	Population	City/Town/ Village in Japanese	City/Town/ Village in English	Node No	Prefecture	Population	Distance（KM）	Travel time（Hour）	information on March 12 2011	information on March 18 2011	information on April 11 2011	information on June 11 2011
49	気仙沼市	Kesennuma	18	Miyagi	73,494	石巻市	Ishinomaki	28	Miyagi	1,60,704	79.8	2.2	×	×	×	×
50	石巻市	Ishinomaki	28	Miyagi	1,60,704	登米市	Tome	20	Miyagi	83,973	42.6	1.1	×	○	○	○
51	石巻市	Ishinomaki	28	Miyagi	1,60,704	大崎市	Osaki	29	Miyagi	1,35,127	35.8	1.2	○	○	○	○
52	大崎市	Osaki	29	Miyagi	1,35,127	塩竈市	Shiogama City	30	Miyagi	56,490	53.5	1.2	○	○	○	○
53	塩竈市	Shiogama City	30	Miyagi	56,490	石巻市	Ishinomaki	28	Miyagi	1,60,704	32.0	0.7	×	×	○	○
54	塩竈市	Shiogama City	30	Miyagi	56,490	多賀城市	Tagajo	31	Miyagi	62,979	3.8	0.1	×	×	○	○
55	塩竈市	Shiogama City	30	Miyagi	56,490	仙台市	Sendai	32	Miyagi	10,45,903	17.3	0.5	×	×	○	○
56	多賀城市	Tagajo	31	Miyagi	62,979	仙台市	Sendai	32	Miyagi	10,45,903	13.5	0.4	×	×	○	○
57	多賀城市	Tagajo	31	Miyagi	62,979	名取市	Natori	33	Miyagi	73,140	20.9	0.5	×	×	○	○
58	仙台市	Sendai	32	Miyagi	10,45,903	名取市	Natori	33	Miyagi	73,140	15.4	0.4	○	○	○	○
59	名取市	Natori	33	Miyagi	73,140	相馬市	Soma	34	Fukushima	37,796	44.6	1.3	×	○	○	○
60	名取市	Natori	33	Miyagi	73,140	大河原町	Okawara town	35	Miyagi	23,530	21.8	0.6	○	○	○	○
61	大河原町	Okawara town	35	Miyagi	23,530	相馬市	Soma	34	Fukushima	37,796	49.5	1.4	○	○	○	○
62	大河原町	Okawara town	35	Miyagi	23,530	伊達市	Date City	36	Fukushima	66,081	43.4	1.2	○	○	○	○
63	仙台市	Sendai	32	Miyagi	10,45,903	大河原町	Okawara town	35	Miyagi	23,530	32.9	0.9	○	○	○	○
64	仙台市	Sendai	32	Miyagi	10,45,903	山形市	Yamagata	37	Yamagata	2,54,084	69.0	1.3	×	×	○	○
65	仙台市	Sendai	32	Miyagi	10,45,903	天童市	Tendo	38	Yamagata	62,225	78.9	1.5	○	○	○	○
66	仙台市	Sendai	32	Miyagi	10,45,903	東根市	Higashine	39	Yamagata	46,412	90.7	1.6	○	○	○	○
67	大崎市	Osaki	29	Miyagi	1,35,127	東根市	Higashine	39	Yamagata	46,412	127.0	2.2	×	○	○	○
68	仙台市	Sendai	32	Miyagi	10,45,903	大崎市	Osaki	29	Miyagi	1,35,127	42.6	0.8	○	○	○	○
69	大崎市	Osaki	29	Miyagi	1,35,127	栗原市	Kurihara	21	Miyagi	74,938	22.6	0.4	○	○	○	○
70	大崎市	Osaki	29	Miyagi	1,35,127	登米市	Tome	20	Miyagi	83,973	34.9	1.0	○	○	○	○
71	登米市	Tome	20	Miyagi	83,973	栗原市	Kurihara	21	Miyagi	74,938	22.1	0.6	○	○	○	○
72	伊達市	Date City	36	Fukushima	66,081	相馬市	Soma	34	Fukushima	37,796	47.0	1.3	○	○	○	○
73	相馬市	Soma	34	Fukushima	37,796	福島市	Fukushima	40	Fukushima	2,92,280	55.0	1.6	○	○	○	○
74	相馬市	Soma	34	Fukushima	37,796	南相馬市	Minamisoma	41	Fukushima	70,895	19.7	0.6	×	○	○	○
75	南相馬市	Minamisoma	41	Fukushima	70,895	いわき市	Iwaki	42	Fukushima	3,42,198	74.8	2.1	×	×	×	×
76	南相馬市	Minamisoma	41	Fukushima	70,895	福島市	Fukushima	40	Fukushima	2,92,280	72.9	2.1	×	○	○	○
77	二本松市	Nihonmatsu	41	Fukushima	59,866	南相馬市	Minamisoma	41	Fukushima	70,895	83.9	2.4	×	×	×	○
78	いわき市	Iwaki	42	Fukushima	3,42,198	二本松市	Nihonmatsu	43	Fukushima	59,866	106.9	1.9	×	×	○	○
79	いわき市	Iwaki	42	Fukushima	3,42,198	郡山市	Koriyama	44	Fukushima	3,38,772	98.9	1.8	○	○	○	○
80	いわき市	Iwaki	42	Fukushima	3,42,198	須賀川市	Sukagawa	45	Fukushima	79,279	114.6	2.1	○	○	○	○
81	いわき市	Iwaki	42	Fukushima	3,42,198	白河市	Shirakawa	46	Fukushima	79,279	136.8	2.6	×	○	○	○
82	白河市	Shirakawa	46	Fukushima	64,710	須賀川市	Sukagawa	45	Fukushima	79,279	26.9	0.6	○	○	○	○
83	白河市	Shirakawa	46	Fukushima	64,710	南会津町	Minamiaizu town	47	Fukushima	20,248	54.4	1.6	○	○	○	○
84	須賀川市	Sukagawa	45	Fukushima	64,710	南会津町	Minamiaizu town	47	Fukushima	20,248	83.5	2.0	×	○	○	○
85	須賀川市	Sukagawa	45	Fukushima	64,710	郡山市	Koriyama	44	Fukushima	3,38,772	13.0	0.4	○	○	○	○
86	郡山市	Koriyama	44	Fukushima	3,38,772	南会津町	Minamiaizu town	47	Fukushima	20,248	103.6	2.4	×	○	○	○
87	郡山市	Koriyama	44	Fukushima	3,38,772	会津若松市	Aizuwakamatsu	48	Fukushima	1,26,125	59.4	1.1	×	×	○	○
88	郡山市	Koriyama	44	Fukushima	3,38,772	二本松市	Nihonmatsu	43	Fukushima	59,866	25.7	0.5	○	○	○	○
89	会津若松市	Aizuwakamatsu	48	Fukushima	1,26,125	南会津町	Minamiaizu town	47	Fukushima	20,248	44.2	1.3	○	○	○	○
90	会津若松市	Aizuwakamatsu	48	Fukushima	1,26,125	喜多方市	Kitakata	49	Fukushima	52,373	19.5	0.6	○	○	○	○
91	喜多方市	Kitakata	49	Fukushima	52,373	二本松市	Nihonmatsu	43	Fukushima	59,866	78.5	1.5	×	×	○	○
92	福島市	Fukushima	40	Fukushima	2,92,280	会津若松市	Aizuwakamatsu	48	Fukushima	1,26,125	92.3	1.7	×	×	○	○
93	福島市	Fukushima	40	Fukushima	2,92,280	二本松市	Nihonmatsu	43	Fukushima	59,866	26.6	0.5	○	○	○	○
94	福島市	Fukushima	40	Fukushima	2,92,280	喜多方市	Kitakata	49	Fukushima	52,373	103.5	2.0	○	○	○	○
95	福島市	Fukushima	40	Fukushima	2,92,280	伊達市	Date City	36	Fukushima	66,081	13.2	0.4	○	○	○	○
96	福島市	Fukushima	40	Fukushima	2,92,280	米沢市	Yonezawa	50	Yamagata	89,392	43.2	1.2	○	○	○	○
97	伊達市	Date City	36	Fukushima	66,081	米沢市	Yonezawa	50	Yamagata	89,392	56.4	1.6	○	○	○	○
98	酒田市	Sakata	52	Yamagata	2,54,084	由利本荘市	Yurihonjo	61	Akita	85,230	65.7	1.7	○	○	○	○
99	酒田市	Sakata	52	Yamagata	2,54,084	湯沢市	Yuzawa	23	Akita	50,863	107.4	2.8	○	○	○	○

Data source: 1. Road information: Road Bureau MLIT, Japan
2. Population: Statistical year book 2012, Japan

Link NO	From					TO					can pass : ○、cannot pass : ×					
	City/Town/ Village in Japanese	City/Town/ Village in English	Node No	Prefecture	Population	City/Town/ Village in Japanese	City/Town/ Village in English	Node No	Prefecture	Population	Distance (KM)	Travel time (Hour)	information on March 12 2011	information on March 18 2011	information on April 11 2011	information on June 11 2011
100	新庄市	Shinjo	22	Yamagata	38,856	湯沢市	Yuzawa	23	Akita	50,863	59.6	1.5	○	○	○	○
101	新庄市	Shinjo	22	Yamagata	38,856	栗原市	Kurihara	21	Miyagi	74,938	79.1	2.3	○	○	○	○
102	新庄市	Shinjo	22	Yamagata	38,856	大崎市	Osaki	29	Miyagi	1,35,127	78.3	2.0	○	○	○	○
103	新庄市	Shinjo	22	Yamagata	38,856	東根市	Higashine	39	Yamagata	46,412	41.0	1.0	○	○	○	○
104	東根市	Higashine	39	Yamagata	46,412	天童市	Tendo	38	Yamagata	62,225	6.1	0.2	○	○	○	○
105	天童市	Tendo	38	Yamagata	62,225	山形市	Yamagata	37	Yamagata	2,54,084	23.9	0.6	○	○	○	○
106	山形市	Yamagata	37	Yamagata	2,54,084	大河原町	Okawara town	35	Miyagi	23,530	68.5	1.3	×	×	○	○
107	山形市	Yamagata	37	Yamagata	2,54,084	伊達市	Date City	36	Fukushima	66,081	92.0	2.0	×	○	○	○
108	山形市	Yamagata	37	Yamagata	2,54,084	米沢市	Yonezawa	50	Yamagata	89,392	52.1	1.4	○	○	○	○
109	米沢市	Yonezawa	50	Yamagata	89,392	喜多方市	Kitakata	49	Fukushima	52,373	144.8	3.0	×	○	○	○
110	鶴岡市	Tsuruoka	51	Yamagata	1,36,627	喜多方市	Kitakata	49	Fukushima	52,373	293.1	5.2	○	○	○	○
111	鶴岡市	Tsuruoka	51	Yamagata	1,36,627	米沢市	Yonezawa	50	Yamagata	89,392	150.7	3.1	○	○	○	○
112	鶴岡市	Tsuruoka	51	Yamagata	1,36,627	山形市	Yamagata	37	Yamagata	2,54,084	98.7	2.0	○	○	○	○
113	鶴岡市	Tsuruoka	51	Yamagata	1,36,627	天童市	Tendo	38	Yamagata	62,225	105.0	2.0	○	○	○	○
114	鶴岡市	Tsuruoka	51	Yamagata	1,36,627	東根市	Higashine	39	Yamagata	46,412	93.1	2.0	○	○	○	○
115	鶴岡市	Tsuruoka	51	Yamagata	1,36,627	新庄市	Shinjo	22	Yamagata	38,856	51.4	1.4	○	○	○	○
116	新庄市	Shinjo	22	Yamagata	38,856	酒田市	Sakata	52	Yamagata	1,11,170	66.5	1.9	○	○	○	○
117	酒田市	Sakata	52	Yamagata	1,11,170	三川町	Mikawa town	53	Yamagata	7,771	25.3	0.7	○	○	○	○
118	酒田市	Sakata	52	Yamagata	1,11,170	鶴岡市	Tsuruoka	51	Yamagata	1,36,627	32.8	0.9	○	○	○	○
119	能代市	Noshiro	54	Akita	59,095	弘前市	Hirosaki	9	Aomori	1,83,534	98.5	2.5	○	○	○	○
120	北秋田市	City Kitaakita	55	Akita	36,397	五所川原市	Goshogawara	10	Aomori	58,423	97.1	2.1	○	○	○	○
121	北秋田市	City Kitaakita	55	Akita	36,397	弘前市	Hirosaki	9	Aomori	1,83,534	61.2	1.6	○	○	○	○
122	大館市	Odate	8	Akita	78,951	弘前市	Hirosaki	9	Aomori	1,83,534	44.6	1.1	○	○	○	○
123	大館市	Odate	8	Akita	78,951	鹿角市	Kazuno	7	Akita	34,479	40.2	1.2	○	○	○	○
124	大館市	Odate	8	Akita	78,951	北秋田市	City Kitaakita	55	Akita	36,397	18.4	0.5	○	○	○	○
125	大館市	Odate	8	Akita	78,951	秋田市	Akita	26	Akita	3,23,363	109.4	2.5	○	○	○	○
126	秋田市	Akita	26	Akita	3,23,363	北秋田市	City Kitaakita	55	Akita	36,397	91.1	1.9	○	○	○	○
127	秋田市	Akita	26	Akita	3,23,363	大仙市	Daisen	25	Akita	88,299	59.5	1.2	○	○	○	○
128	大仙市	Daisen	25	Akita	88,299	由利本荘市	Yurihonjo	61	Akita	85,230	85.4	1.5	○	○	○	○
129	大仙市	Daisen	25	Akita	88,299	横手市	Yokote	24	Akita	98,379	35.6	0.7	○	○	○	○
130	横手市	Yokote	24	Akita	98,379	由利本荘市	Yurihonjo	61	Akita	85,230	52.3	1.5	○	○	○	○
131	横手市	Yokote	24	Akita	98,379	湯沢市	Yuzawa	23	Akita	50,863	16.9	0.3	○	○	○	○
132	湯沢市	Yuzawa	23	Akita	98,379	由利本荘市	Yurihonjo	61	Akita	85,230	55.3	1.6	○	○	○	○
133	由利本荘市	Yurihonjo	61	Akita	85,230	秋田市	Akita	26	Akita	3,23,363	56.0	1.1	○	○	○	○
134	秋田市	Akita	26	Akita	3,23,363	男鹿市	Oga	56	Akita	32,319	35.1	1.0	○	○	○	○
135	秋田市	Akita	26	Akita	88,299	能代市	Noshiro	54	Akita	59,095	62.8	1.3	○	○	○	○
136	男鹿市	Oga	56	Akita	32,319	能代市	Noshiro	54	Akita	59,095	51.2	1.4	○	○	○	○
137	能代市	Noshiro	54	Akita	59,095	北秋田市	City Kitaakita	55	Akita	36,397	37.4	0.9	○	○	○	○
138	鶴岡市	Tsuruoka	61	Yamagata	1,36,627	村上市	Murakami	57	Akita	66,445	88.0	2.5	○	○	○	○
139	喜多方市	Kitakata	49	Fukushima	52,373	村上市	Murakami	57	Akita	66,445	158.3	3.6	○	○	○	○
140	村上市	Murakami	57	Nigata	66,445	新潟市	Niigata	58	Akita	8,12,192	71.1	1.7	○	○	○	○
141	村上市	Murakami	57	Nigata	66,445	米沢市	Yonezawa	50	Yamagata	89,392	95.7	2.7	○	○	○	○
142	新潟市	Niigata	58	Nigata	8,12,192	喜多方市	Kitakata	49	Fukushima	52,373	120.6	2.3	×	×	○	○
143	新庄市	Shinjo	22	Nigata	1,02,309	三川町	Mikawa town	53	Yamagata	7,771	59.0	1.6	○	○	○	○
144	南会津町	Minamiaizu town	47	Fukushima	20,248	那須塩原市	Nasushiobara	59	Tochigi	1,17,706	63.4	1.8	○	○	○	○
145	白河市	Shirakawa	46	Fukushima	64,710	那須塩原市	Nasushiobara	59	Tochigi	1,17,706	34.5	1.0	○	○	○	○
146	日立市	Hitachi City	60	Ibaraki	1,93,129	那須塩原市	Nasushiobara	59	Tochigi	1,17,706	101.3	2.9	○	○	○	○
147	いわき市	Iwaki	42	Fukushima	3,42,198	日立市	Hitachi City	60	Fukushima	1,93,129	72.7	1.4	×	×	○	○
148	白河市	Shirakawa	46	Fukushima	64,710	日立市	Hitachi City	60	Fukushima	1,93,129	114.0	2.9	×	○	○	○
149	湯沢市	Yuzawa	23	Akita	50,863	大崎市	Osaki	29	Miyagi	1,35,127	155.3	2.6	○	○	○	○

Data source: 1. Road information: Road Bureau MLIT, Japan
2. Population: Statistical year book 2012, Japan

Appendix B: Priority list of links based on change in accessibility index of the all links analysis from existing model (Taylor, Sekhar et al. 2006)'s method (Tohoku Region, Japan)

Priority No	Link NO	From	TO	Change in accessibility index
1	58	Sendai	Natori	0.0114
2	45	Morioka	Takizawa	0.0111
3	56	Tagajo	Sendai	0.0085
4	95	Fukushima	Date City	0.0058
5	93	Fukushima	Nihonmatsu	0.0049
6	68	Sendai	Osaki	0.0032
7	105	Tendo	Yamagata	0.0029
8	134	Akita	Oga	0.0027
9	53	Shiogama City	Ishinomaki	0.0026
10	140	Murakami	Niigata	0.0026
11	104	Higashine	Tendo	0.0025
12	85	Sukagawa	Koriyama	0.0024
13	88	Koriyama	Nihonmatsu	0.0024
14	74	Soma	Minamisoma	0.0022
15	69	Osaki	Kurihara	0.0018
16	59	Natori	Soma	0.0015
17	82	Shirakawa	Sukagawa	0.0014
18	43	Morioka	Hanamaki	0.0013
19	62	Okawara town	Date City	0.0012
20	108	Yamagata	Yonezawa	0.0012
21	133	Yurihonjo	Akita	0.0012
22	63	Sendai	Okawara town	0.0011
23	14	Aomori	Goshogawara	0.001
24	39	Kitakami	Hanamaki	0.001
25	127	Akita	Daisen	0.001
26	142	Niigata	Kitakata	0.001
27	34	Ichinoseki	Oshu	0.0009
28	90	Aizuwakamatsu	Kitakata	0.0009
29	9	Aomori	Towada	0.0008
30	36	Oshu	Kitakami	0.0008
31	96	Fukushima	Yonezawa	0.0008
32	138	Tsuruoka	Murakami	0.0008
33	145	Shirakawa	Nasushiobara	0.0008
34	75	Minamisoma	Iwaki	0.0007
35	103	Shinjo	Higashine	0.0007
36	115	Tsuruoka	Shinjo	0.0007
37	3	Aomori	Rokkasho-mura	0.0006
38	12	Aomori	Hirosaki	0.0006
39	47	Morioka	Kazuno	0.0006
40	65	Sendai	Tendo	0.0006
41	89	Aizuwakamatsu	Minamiaizu town	0.0006
42	135	Akita	Noshiro	0.0006
43	141	Murakami	Yonezawa	0.0006
44	143	Shinjo	Mikawa town	0.0006
45	31	Ichinoseki	Kurihara	0.0005
46	70	Osaki	Tome	0.0005
47	16	Morioka	Hachinohe	0.0004
48	27	Ofunato	Kesennuma	0.0004
49	42	Morioka	Daisen	0.0004

50	92	Fukushima	Aizuwakamatsu	0.0004
51	106	Yamagata	Okawara town	0.0004
52	123	Odate	Kazuno	0.0004
53	147	Iwaki	Hitachi City	0.0004
54	1	Aomori	Mutsu	0.0003
55	4	Rokkasho-mura	Hachinohe	0.0003
56	15	Kuji	Hachinohe	0.0003
57	19	Morioka	Miyako	0.0003
58	20	Miyako	Kamaishi	0.0003
59	24	Kamaishi	Ofunato	0.0003
60	60	Natori	Okawara town	0.0003
61	64	Sendai	Yamagata	0.0003
62	100	Shinjo	Yuzawa	0.0003
63	124	Odate	City Kitaakita	0.0003
64	10	Aomori	Kazuno	0.0002
65	17	Morioka	Kuji	0.0002
66	21	Morioka	Kamaishi	0.0002
67	38	Kitakami	Yokote	0.0002
68	73	Soma	Fukushima	0.0002
69	98	Sakata	Yurihonjo	0.0002
70	107	Yamagata	Date City	0.0002
71	112	Tsuruoka	Yamagata	0.0002
72	116	Shinjo	Sakata	0.0002
73	118	Sakata	Tsuruoka	0.0002
74	126	Akita	City Kitaakita	0.0002
75	131	Yokote	Yuzawa	0.0002
76	2	Mutsu	Rokkasho-mura	0.0001
77	7	Towada	Morioka	0.0001
78	8	Towada	Kazuno	0.0001
79	11	Aomori	Odate	0.0001
80	13	Hirosaki	Goshogawara	0.0001
81	18	Kuji	Miyako	0.0001
82	28	Kesennuma	Oshu	0.0001
83	30	Ichinoseki	Tome	0.0001
84	37	Oshu	Yokote	0.0001
85	49	Kesennuma	Ishinomaki	0.0001
86	51	Ishinomaki	Osaki	0.0001
87	61	Okawara town	Soma	0.0001
88	71	Tome	Kurihara	0.0001
89	78	Iwaki	Nihonmatsu	0.0001
90	87	Koriyama	Aizuwakamatsu	0.0001
91	91	Kitakata	Nihonmatsu	0.0001
92	101	Shinjo	Kurihara	0.0001
93	102	Shinjo	Osaki	0.0001
94	122	Odate	Hirosaki	0.0001
95	129	Daisen	Yokote	0.0001
96	130	Yokote	Yurihonjo	0.0001
97	132	Yuzawa	Yurihonjo	0.0001
98	136	Oga	Noshiro	0.0001
99	137	Noshiro	City Kitaakita	0.0001
100	144	Minamiaizu town	Nasushiobara	0.0001
101	5	Aomori	Hachinohe	0
102	6	Hachinohe	Towada	0
103	22	Kamaishi	Hanamaki	0
104	23	Kamaishi	Kitakami	0
105	25	Ofunato	Kitakami	0

106	26	Ofunato	Oshu	0
107	29	Kesennuma	Ichinoseki	0
108	32	Ichinoseki	Shinjo	0
109	33	Ichinoseki	Yuzawa	0
110	35	Oshu	Yuzawa	0
111	40	Hanamaki	Yokote	0
112	41	Morioka	Yokote	0
113	44	Morioka	Akita	0
114	46	Morioka	Odate	0
115	48	Kesennuma	Tome	0
116	50	Ishinomaki	Tome	0
117	52	Osaki	Shiogama City	0
118	54	Shiogama City	Tagajo	0
119	55	Shiogama City	Sendai	0
120	57	Tagajo	Natori	0
121	66	Sendai	Higashine	0
122	67	Osaki	Higashine	0
123	72	Date City	Soma	0
124	76	Minamisoma	Fukushima	0
125	77	Nihonmatsu	Minamisoma	0
126	79	Iwaki	Koriyama	0
127	80	Iwaki	Sukagawa	0
128	81	Iwaki	Shirakawa	0
129	83	Shirakawa	Minamiaizu town	0
130	84	Sukagawa	Minamiaizu town	0
131	86	Koriyama	Minamiaizu town	0
132	94	Fukushima	Kitakata	0
133	97	Date City	Yonezawa	0
134	99	Sakata	Yuzawa	0
135	109	Yonezawa	Kitakata	0
136	110	Tsuruoka	Kitakata	0
137	111	Tsuruoka	Yonezawa	0
138	113	Tsuruoka	Tendo	0
139	114	Tsuruoka	Higashine	0
140	117	Sakata	Mikawa town	0
141	119	Noshiro	Hirosaki	0
142	120	City Kitaakita	Goshogawara	0
143	121	City Kitaakita	Hirosaki	0
144	125	Odate	Akita	0
145	128	Daisen	Yurihonjo	0
146	139	Kitakata	Murakami	0
147	146	Hitachi City	Nasushiobara	0
148	148	Shirakawa	Hitachi City	0
149	149	Yuzawa	Osaki	0

Appendix C: Priority list of links based on increase in travel time(degree of weakness) existing methodology from MLIT 2011b (Tohoku Region, Japan)

Priority No	Link NO	From	TO	Index (Degree of Weakness
1	142	Niigata	Kitakata	1.0187
2	47	Morioka	Kazuno	1.0101
3	10	Aomori	Kazuno	1.0086
4	16	Morioka	Hachinohe	1.0066
5	64	Sendai	Yamagata	1.0064
6	74	Soma	Minamisoma	1.0056
7	147	Iwaki	Hitachi City	1.0039
8	41	Morioka	Yokote	1.0032
9	4	Rokkasho-mura	Hachinohe	1.0029
10	59	Natori	Soma	1.0029
11	107	Yamagata	Date City	1.0025
12	53	Shiogama City	Ishinomaki	1.002
13	92	Fukushima	Aizuwakamatsu	1.0018
14	106	Yamagata	Okawara town	1.0017
15	78	Iwaki	Nihonmatsu	1.0016
16	3	Aomori	Rokkasho-mura	1.0014
17	75	Minamisoma	Iwaki	1.0013
18	20	Miyako	Kamaishi	1.0012
19	19	Morioka	Miyako	1.001
20	38	Kitakami	Yokote	1.0009
21	27	Ofunato	Kesennuma	1.0008
22	37	Oshu	Yokote	1.0008
23	57	Tagajo	Natori	1.0007
24	21	Morioka	Kamaishi	1.0005
25	54	Shiogama City	Tagajo	1.0005
26	87	Koriyama	Aizuwakamatsu	1.0005
27	46	Morioka	Odate	1.0004
28	56	Tagajo	Sendai	1.0004
29	91	Kitakata	Nihonmatsu	1.0004
30	23	Kamaishi	Kitakami	1.0003
31	24	Kamaishi	Ofunato	1.0003
32	30	Ichinoseki	Tome	1.0003
33	49	Kesennuma	Ishinomaki	1.0001
34	55	Shiogama City	Sendai	1
35	50	Ishinomaki	Tome	1
36	40	Hanamaki	Yokote	1
37	48	Kesennuma	Tome	1
38	33	Ichinoseki	Yuzawa	1
39	84	Sukagawa	Minamiaizu town	1
40	76	Minamisoma	Fukushima	1
41	22	Kamaishi	Hanamaki	1
42	67	Osaki	Higashine	1
43	86	Koriyama	Minamiaizu town	1
44	77	Nihonmatsu	Minamisoma	1
45	81	Iwaki	Shirakawa	1
46	18	Kuji	Miyako	1
47	148	Shirakawa	Hitachi City	1
48	109	Yonezawa	Kitakata	1

Appendix D: Priority list of closed links based on change in accessibility index analysis from first modification on the existing model (Taylor, Sekhar et al. 2006)'s method (Tohoku Region, Japan)

Priority No	Link NO	From	TO	Change in accessibility index
1	56	Tagajo	Sendai	0.0085
2	53	Shiogama City	Ishinomaki	0.0026
3	74	Soma	Minamisoma	0.0022
4	59	Natori	Soma	0.0015
5	142	Niigata	Kitakata	0.001
6	75	Minamisoma	Iwaki	0.0007
7	3	Aomori	Rokkasho-mura	0.0006
8	47	Morioka	Kazuno	0.0006
9	16	Morioka	Hachinohe	0.0004
10	27	Ofunato	Kesennuma	0.0004
11	92	Fukushima	Aizuwakamatsu	0.0004
12	106	Yamagata	Okawara town	0.0004
13	147	Iwaki	Hitachi City	0.0004
14	4	Rokkasho-mura	Hachinohe	0.0003
15	19	Morioka	Miyako	0.0003
16	20	Miyako	Kamaishi	0.0003
17	24	Kamaishi	Ofunato	0.0003
18	64	Sendai	Yamagata	0.0003
19	10	Aomori	Kazuno	0.0002
20	21	Morioka	Kamaishi	0.0002
21	38	Kitakami	Yokote	0.0002
22	107	Yamagata	Date City	0.0002
23	18	Kuji	Miyako	0.0001
24	30	Ichinoseki	Tome	0.0001
25	37	Oshu	Yokote	0.0001
26	49	Kesennuma	Ishinomaki	0.0001
27	78	Iwaki	Nihonmatsu	0.0001
28	87	Koriyama	Aizuwakamatsu	0.0001
29	91	Kitakata	Nihonmatsu	0.0001
30	22	Kamaishi	Hanamaki	0
31	23	Kamaishi	Kitakami	0
32	33	Ichinoseki	Yuzawa	0
33	40	Hanamaki	Yokote	0
34	41	Morioka	Yokote	0
35	46	Morioka	Odate	0
36	48	Kesennuma	Tome	0
37	50	Ishinomaki	Tome	0
38	54	Shiogama City	Tagajo	0
39	55	Shiogama City	Sendai	0
40	57	Tagajo	Natori	0
41	67	Osaki	Higashine	0
42	76	Minamisoma	Fukushima	0
43	77	Nihonmatsu	Minamisoma	0
44	81	Iwaki	Shirakawa	0
45	84	Sukagawa	Minamiaizu town	0
46	86	Koriyama	Minamiaizu town	0
47	109	Yonezawa	Kitakata	0
48	148	Shirakawa	Hitachi City	0

AppendixE: Priority list of closed links analysis from second modification on the existing model (Taylor, Sekhar et al. 2006)'s method (Tohoku Region, Japan)

Priority No	Link NO	From	TO	Remarks
1	56	Tagajo	Sendai	
2	54	Shiogama City	Tagajo	
3	55	Shiogama City	Sendai	
4	74	Soma	Minamisoma	
5	22	Kamaishi	Hanamaki	
6	19	Morioka	Miyako	
7	142	Niigata	Kitakata	
8	53	Shiogama City	Ishinomaki	
9	59	Natori	Soma	
10	64	Sendai	Yamagata	
11	47	Morioka	Kazuno	
12	38	Kitakami	Yokote	
13	87	Koriyama	Aizuwakamatsu	
14	75	Minamisoma	Iwaki	
15	3	Aomori	Rokkasho-mura	
16	10	Aomori	Kazuno	
17	106	Yamagata	Okawara town	
18	92	Fukushima	Aizuwakamatsu	
19	147	Iwaki	Hitachi City	
20	16	Morioka	Hachinohe	
21	49	Kesennuma	Ishinomaki	
22	27	Ofunato	Kesennuma	
23	4	Rokkasho-mura	Hachinohe	
24	24	Kamaishi	Ofunato	
25	20	Miyako	Kamaishi	
26	21	Morioka	Kamaishi	
27	41	Morioka	Yokote	
28	107	Yamagata	Date City	
29	91	Kitakata	Nihonmatsu	
30	37	Oshu	Yokote	
31	78	Iwaki	Nihonmatsu	
32	57	Tagajo	Natori	
33	30	Ichinoseki	Tome	
34	18	Kuji	Miyako	
35	23	Kamaishi	Kitakami	
36	50	Ishinomaki	Tome	
37	76	Minamisoma	Fukushima	
38	46	Morioka	Odate	
39	109	Yonezawa	Kitakata	
40	40	Hanamaki	Yokote	
41	48	Kesennuma	Tome	
42	33	Ichinoseki	Yuzawa	
43	84	Sukagawa	Minamiaizu town	
44	67	Osaki	Higashine	
45	86	Koriyama	Minamiaizu town	
46	77	Nihonmatsu	Minamisoma	
47	81	Iwaki	Shirakawa	
48	148	Shirakawa	Hitachi City	

Appendix F: Priority list of closed links analysis from the new proposed methodology at Detour ratio 1.5 based on information of Tohoku regional road network immediately after disaster

Priority No	Link NO	From	TO	Remarks
1	56	Tagajo	Sendai	Important for the connection
2	74	Soma	Minamisoma	
3	19	Morioka	Miyako	
4	22	Kamaishi	Hanamaki	
5	54	Shiogama City	Tagajo	Important for the Network optimization
6	55	Shiogama City	Sendai	
7	53	Shiogama City	Ishinomaki	
8	75	Minamisoma	Iwaki	
9	142	Niigata	Kitakata	
10	47	Morioka	Kazuno	
11	59	Natori	Soma	
12	64	Sendai	Yamagata	
13	87	Koriyama	Aizuwakamatsu	
14	147	Iwaki	Hitachi City	
15	16	Morioka	Hachinohe	
16	38	Kitakami	Yokote	
17	92	Fukushima	Aizuwakamatsu	
18	3	Aomori	Rokkasho-mura	
19	10	Aomori	Kazuno	
20	106	Yamagata	Okawara town	
21	78	Iwaki	Nihonmatsu	
22	49	Kesennuma	Ishinomaki	
23	4	Rokkasho-mura	Hachinohe	
24	27	Ofunato	Kesennuma	
25	41	Morioka	Yokote	
26	37	Oshu	Yokote	
27	24	Kamaishi	Ofunato	
28	20	Miyako	Kamaishi	
29	107	Yamagata	Date City	
30	21	Morioka	Kamaishi	
31	91	Kitakata	Nihonmatsu	
32	57	Tagajo	Natori	
33	30	Ichinoseki	Tome	
34	50	Ishinomaki	Tome	
35	18	Kuji	Miyako	
36	76	Minamisoma	Fukushima	
37	46	Morioka	Odate	
38	23	Kamaishi	Kitakami	
39	109	Yonezawa	Kitakata	
40	40	Hanamaki	Yokote	
41	48	Kesennuma	Tome	
42	33	Ichinoseki	Yuzawa	
43	84	Sukagawa	Minamiaizu town	
44	67	Osaki	Higashine	
45	86	Koriyama	Minamiaizu town	
46	77	Nihonmatsu	Minamisoma	
47	81	Iwaki	Shirakawa	
48	148	Shirakawa	Hitachi City	

Appendix G: Priority list of closed links analysis from the new proposed methodology at Detour ratio 2 based on information of Tohoku regional road network immediately after disaster

Priority No	Link NO	From	TO	Remarks
1	56	Tagajo	Sendai	Important for the connection
2	74	Soma	Minamisoma	
3	19	Morioka	Miyako	
4	22	Kamaishi	Hanamaki	
5	54	Shiogama City	Tagajo	Important for the Network optimization
6	55	Shiogama City	Sendai	
7	53	Shiogama City	Ishinomaki	
8	142	Niigata	Kitakata	
9	87	Koriyama	Aizuwakamatsu	
10	75	Minamisoma	Iwaki	
11	59	Natori	Soma	
12	64	Sendai	Yamagata	
13	47	Morioka	Kazuno	
14	147	Iwaki	Hitachi City	
15	16	Morioka	Hachinohe	
16	38	Kitakami	Yokote	
17	92	Fukushima	Aizuwakamatsu	
18	10	Aomori	Kazuno	
19	106	Yamagata	Okawara town	
20	3	Aomori	Rokkasho-mura	
21	78	Iwaki	Nihonmatsu	
22	49	Kesennuma	Ishinomaki	
23	4	Rokkasho-mura	Hachinohe	
24	27	Ofunato	Kesennuma	
25	41	Morioka	Yokote	
26	37	Oshu	Yokote	
27	24	Kamaishi	Ofunato	
28	20	Miyako	Kamaishi	
29	107	Yamagata	Date City	
30	21	Morioka	Kamaishi	
31	91	Kitakata	Nihonmatsu	
32	57	Tagajo	Natori	
33	30	Ichinoseki	Tome	
34	50	Ishinomaki	Tome	
35	18	Kuji	Miyako	
36	76	Minamisoma	Fukushima	
37	46	Morioka	Odate	
38	23	Kamaishi	Kitakami	
39	109	Yonezawa	Kitakata	
40	40	Hanamaki	Yokote	
41	48	Kesennuma	Tome	
42	33	Ichinoseki	Yuzawa	
43	84	Sukagawa	Minamiaizu town	
44	67	Osaki	Higashine	
45	86	Koriyama	Minamiaizu town	
46	77	Nihonmatsu	Minamisoma	
47	81	Iwaki	Shirakawa	
48	148	Shirakawa	Hitachi City	

Appendix H: Priority list of closed links analysis from the new proposed methodology at Detour ratio 1.5 based on information of Tohoku regional road network one week after disaster

Priority No	Link NO	From	TO	Remarks
1	56	Tagajo	Sendai	Important for the connection
2	19	Morioka	Miyako	
3	54	Shiogama City	Tagajo	Important for the network performancew
4	55	Shiogama City	Sendai	
5	53	Shiogama City	Ishinomaki	
6	75	Minamisoma	Iwaki	
7	142	Niigata	Kitakata	
8	47	Morioka	Kazuno	
9	64	Sendai	Yamagata	
10	87	Koriyama	Aizuwakamatsu	
11	16	Morioka	Hachinohe	
12	147	Iwaki	Hitachi City	
13	38	Kitakami	Yokote	
14	92	Fukushima	Aizuwakamatsu	
15	10	Aomori	Kazuno	
16	106	Yamagata	Okawara town	
17	78	Iwaki	Nihonmatsu	
18	27	Ofunato	Kesennuma	
19	20	Miyako	Kamaishi	
20	41	Morioka	Yokote	
21	37	Oshu	Yokote	
22	91	Kitakata	Nihonmatsu	
23	49	Kesennuma	Ishinomaki	
24	57	Tagajo	Natori	
25	18	Kuji	Miyako	
26	46	Morioka	Odate	
27	40	Hanamaki	Yokote	
28	67	Osaki	Higashine	
29	77	Nihonmatsu	Minamisoma	
30	148	Shirakawa	Hitachi City	

Appendix I: Priority list of closed links analysis from the new proposed methodology at Detour ratio 1.5 based on information of Tohoku regional road network immediately after disaster (Without considering the critical population and distance)

Priority No	Link NO	From	TO	Remarks
1	56	Tagajo	Sendai	Important for the connection
2	74	Soma	Minamisoma	
3	19	Morioka	Miyako	
4	22	Kamaishi	Hanamaki	
5	54	Shiogama City	Tagajo	Important for the Network optimization
6	55	Shiogama City	Sendai	
7	53	Shiogama City	Ishinomaki	
8	75	Minamisoma	Iwaki	
9	142	Niigata	Kitakata	
10	47	Morioka	Kazuno	
11	59	Natori	Soma	
12	64	Sendai	Yamagata	
13	87	Koriyama	Aizuwakamatsu	
14	147	Iwaki	Hitachi City	
15	16	Morioka	Hachinohe	
16	38	Kitakami	Yokote	
17	92	Fukushima	Aizuwakamatsu	
18	10	Aomori	Kazuno	
19	78	Iwaki	Nihonmatsu	
20	106	Yamagata	Okawara town	
21	49	Kesennuma	Ishinomaki	
22	3	Aomori	Rokkasho-mura	
23	27	Ofunato	Kesennuma	
24	41	Morioka	Yokote	
25	37	Oshu	Yokote	
26	24	Kamaishi	Ofunato	
27	20	Miyako	Kamaishi	
28	107	Yamagata	Date City	
29	21	Morioka	Kamaishi	
30	4	Rokkasho-mura	Hachinohe	
31	91	Kitakata	Nihonmatsu	
32	57	Tagajo	Natori	
33	30	Ichinoseki	Tome	
34	50	Ishinomaki	Tome	
35	18	Kuji	Miyako	
36	76	Minamisoma	Fukushima	
37	46	Morioka	Odate	
38	23	Kamaishi	Kitakami	
39	109	Yonezawa	Kitakata	
40	40	Hanamaki	Yokote	
41	48	Kesennuma	Tome	
42	33	Ichinoseki	Yuzawa	
43	84	Sukagawa	Minamiaizu town	
44	67	Osaki	Higashine	
45	86	Koriyama	Minamiaizu town	
46	77	Nihonmatsu	Minamisoma	
47	81	Iwaki	Shirakawa	
48	148	Shirakawa	Hitachi City	

Appendix J: Road network information including dry weathered road and all weathered road, Syangja District of Nepal

SNO	From			To			Distance	Condition Dry weather=1, All Weather 2
	Village/City	Population	Node No	Village/City	Population	Node No		
1	Syangja	31325	1	Bahakot	2377	2	6	1
2	Bahakot	2377	2	Kolma	2471	3	5	1
3	Bahakot	2377	2	Oreste	4513	4	5	1
4	Oreste	4513	4	Kitchanas	5880	6	6	1
5	Kitchanas	5880	6	Chisapani	5201	7	4	1
6	Chisapani	5201	7	Chitrebhayang	4292	8	5	1
7	Chitrebhayang	4292	8	Chinnebas	5914	10	7	1
8	Rangkhola	j	11	Rangbhang	4497	5	10	2
9	Rangbhang	4497	5	Biruwa	3506	12	17	1
10	Biruwa	3506	12	Chinnebas	5914	10	7	1
11	Bagalthok	j	14	Pelcachaur	2521	15	8	1
12	Pelcachaur	2521	15	Biruwa	3506	12	17	1
13	Bayarghari	6607	19	Banethok	4475	16	10	1
14	Banethok	4475	16	Pelcachaur	2521	15	4	1
15	Banethok	4475	16	Majhkot	2222	17	4	1
16	Majhkot	2222	17	Manakamana	5795	13	4	1
17	Manakamana	5795	13	Chinnebas	5914	10	6	1
18	Manakamana	5795	13	Biruwa	3506	12	14	1
19	Triyasi	j	20	Majhkot	2222	17	8	1
20	Triyasi	j	20	Yaladi	2442	18	5	1
21	Waling	21555	21	Jagat Bhayangjang	3996	22	7	2
22	Jagat Bhayangjang	3996	22	Malayangkot	6303	23	18	1
23	Malayangkot	6303	23	Chinnebas	5914	10	2	1
24	Malayangkot	6303	23	Shekham	5096	29	5	1
25	Malayangkot	6303	23	Ratnapur	4023	31	12	1
26	Malayangkot	6303	23	Kyakmi	6427	9	10	1
27	Jagat Bhayangjang	3996	22	Kewore	3441	27	6	1

Source: 1. Road infromation : District Technical Office, Syangja,Nepal
2.Population: National Association of VDC's in Nepal

28	Kewore	3441	27	Chhapa	2474	28	7	1
29	Chhapa	2474	28	Kuwakot	2474	33	5	1
30	Chhapa	2474	28	Chapakot	4895	32	6	1
31	Chhapa	2474	28	Ratnapur	4023	31	8	1
32	Shekham	5096	29	Ratnapur	4023	31	6	1
33	Ratnapur	4023	31	Sakhar	5779	30	7	1
34	Tin Dobate1	j	24	Tin Doabte2	4730	25	2	1
35	Tin Doabte2	4730	25	Pakawadi 1	3411	26	7	1
36	Pakawadi 1	3411	26	Chhapa	2474	28	8	1
37	Galayang	8377	36	Tulshi Bhayanjang	4912	35	8	1
38	Tulshi Bhayanjang	4912	35	Pakawadi 2	3411	34	6	1
39	Pakawadi 2	3411	34	Kuwakot	2474	33	7	1
40	Kuwakot	2474	33	Chapakot	4895	32	6	1
41	Chapakot	4895	32	Ratnapur	4023	31	6	1
42	Syangja	31325	1	Rangkhola	j	11	4.4	2
43	Rangkhola	j	11	Bagalthok	j	14	4.9	2
44	Bagalthok	j	14	Helu	6607	51	2.5	2
45	Bayarghari	6607	19	Triyasi	j	20	5	2
46	Triyasi	j	20	Waling	21555	21	3	2
47	Waling	21555	21	Tin Dobate1	j	24	8	2
48	Tin Dobate1	j	24	Tindobate 3	J	37	3	2
49	Banethok	4475	16	Biruwa	3506	12	10	1
50	Oreste	4513	4	Biruwa	3506	12	10	1
51	Tin Dobate3	j	37	Galayang	8377	36	3	2
52	Galayang	8377	36	Malunga	3734	38	5	2
53	Galayang	8377	36	Mirmi	12092	39	23	2
54	Mirmi	12092	39	Birgha	6268	40	9	1
55	Birgha	6268	40	Aalamdevi	4558	41	8	1
56	Aalamdevi	4558	41	Chandi Bhayanjang	5166	42	8	1
57	Galayang	8377	36	Neuwakharka	4823	43	12	1
58	Neuwakharka	4823	43	Pelakot	6585	44	10	1
59	Pelakot	6585	44	Pidikhola	6293	77	14	1
60	Pelakot	6585	44	Tindobate 3	J	37	7	1
61	Tin Dobate1	j	24	Thum Pokhara	6333	45	10	2
62	Thum Pokhara	6333	45	Sirsekot	4714	46	9	1
63	Triyasi	j	20	Sworek	5769	47	6	1
64	Sworek	5769	47	Kalikakot	5682	48	7	1

Source: 1. Road infromation : District Technical Office, Syangja,Nepal
2.Population: National Association of VDC's in Nepal

65	Bayarghari	6607	19	Khilung Deurali	4806	49	5	1
66	Khilung Deurali	4806	49	Dhapuk Shimal Bhayanjang	4511	50	5	1
67	Helu	j	51	Bayarghari	6607	19	2.5	2
68	Helu	J	51	Arjun Chaupari	6770	52	7	1
69	Arjun Chaupari	6770	52	Rapakot	4747	53	7	1
70	Rapakot	4747	53	Aaruchaur	3521	54	7	1
71	Aaruchaur	3521	54	Panchamul	5378	55	8	1
72	Panchamul	5378	55	Daraun	2761	56	9	1
73	Daraun	2761	56	Arjun Chaupari	6770	52	10	1
74	Daraun	2761	56	PBM8	4000	57	10	1
75	PBM8	5000	57	PBM9	2000	58	9	1
76	PBM9	2000	58	Syangja	31325	1	9	1
77	Rangkhola	j	11	PBM10	3500	59	5	1
78	PBM10	3500	59	Arjun Chaupari	6770	52	6	1
79	PBM9	2000	58	Phaparthum	3127	60	6	1
80	Phaparthum	3127	60	Chilaunebash	3446	61	9	1
81	Chilaunebash	3446	61	Bichari Chautara	3077	62	8	1
82	Bichari Chautara	3077	62	Aaruchaur	3521	54	18	1
83	Syangja	31325	1	Naudanda	3000	63	9	2
84	Naudanda	3000	63	Setidovan	3719	64	6	2
85	Setidovan	3719	64	Jugley	j	65	6	2
86	Jugley	j	65	Fulbari	j	66	6	1
87	Fulbari	j	66	Bichari Chautara	3077	62	6	1
88	Jugley	J	65	Chilaunebash	3446	61	5	1
89	Naudanda	3000	63	Khadketari	3515	67	4	2
90	Khadketari	3515	67	Bhadkhola	2203	68	6	1
91	Bhadkhola	2203	68	Bange Fadke	1399	69	6	1
92	Bange Fadke	1399	69	Wangshingh	3128	70	7	1
93	Wangshingh	3128	70	Fulbari	j	66	8	1
94	Khadketari	3515	67	Kubhinde	3515	71	6	2
95	Kubhinde	3515	71	Aarukharka	4029	72	12	1
96	Kubhinde	3515	71	Pawai Gaude	3524	73	20	1
97	Pawai Gaude	3524	73	Taksar	2753	74	9	1
98	Pawai Gaude	3524	73	Naya Bazar	1500	75	5	1
99	Naya Bazar	1500	75	Thula Dihi	3971	76	5	1

Source: 1. Road infromation : District Technical Office, Syangja,Nepal
2.Population: National Association of VDC's in Nepal

Appendix K: Priority list of 'Dry weather links' to upgrades as 'All weathered road' in Syangja District of Nepal analysis from the new proposed methodology

Priority No	Link NO	From	TO	Remarsks
1	63	Triyasi	Sworek	Links important for the Network connection
2	68	Helu	Arjun Chaupari	
3	34	Tin Dobate1	Tin Doabte2	
4	60	Pelakot	Tindobate 3	
5	65	Bayarghari	Khilung Deurali	
6	77	Rangkhola	PBM10	
7	1	Syangja	Bahakot	
8	3	Bahakot	Oreste	
9	4	Oreste	Kitchanas	
10	64	Sworek	Kalikakot	
11	76	PBM9	Syangja	
12	20	Triyasi	Yaladi	
13	2	Bahakot	Kolma	
14	37	Galayang	Tulshi Bhayanjang	
15	13	Bayarghari	Banethok	
16	66	Khilung Deurali	Dhapuk Shimal Bhayanjang	
17	19	Triyasi	Majhkot	
18	16	Majhkot	Manakamana	
19	69	Arjun Chaupari	Rapakot	
20	22	Jagat Bhayangjang	Malayangkot	
21	98	Pawai Gaude	Naya Bazar	
22	11	Bagalthok	Pelcachaur	
23	57	Galayang	Neuwakharka	
24	27	Jagat Bhayangjang	Kewore	
25	79	PBM9	Phaparthum	
26	75	PBM8	PBM9	
27	35	Tin Doabte2	Pakawadi 1	
28	90	Khadketari	Bhadkhola	
29	24	Malayangkot	Shekham	
30	62	Thum Pokhara	Sirsekot	
31	50	Oreste	Biruwa	
32	10	Biruwa	Chinnebas	
33	73	Daraun	Arjun Chaupari	
34	97	Pawai Gaude	Taksar	
35	26	Malayangkot	Kyakmi	
36	38	Tulshi Bhayanjang	Pakawadi 2	
37	70	Rapakot	Aaruchaur	
38	39	Pakawadi 2	Kuwakot	
39	54	Mirmi	Birgha	
40	72	Panchamul	Daraun	
41	80	Phaparthum	Chilaunebash	
42	55	Birgha	Aalamdevi	
43	91	Bhadkhola	Bange Fadke	
44	28	Kewore	Chhapa	
45	81	Chilaunebash	Bichari Chautara	
46	92	Bange Fadke	Wangshingh	
47	95	Kubhinde	Aarukharka	
48	30	Chhapa	Chapakot	

49	31	Chhapa	Ratnapur	
50	33	Ratnapur	Sakhar	
51	5	Kitchanas	Chisapani	
52	56	Aalamdevi	Chandi Bhayanjang	
53	6	Chisapani	Chitrebhayang	
54	99	Naya Bazar	Thula Dihi	
55	59	Pelakot	Pidikhola	
56	23	Malayangkot	Chinnebas	Links important for the Network performance
57	78	PBM10	Arjun Chaupari	
58	17	Manakamana	Chinnebas	
59	7	Chitrebhayang	Chinnebas	
60	29	Chhapa	Kuwakot	
61	32	Shekham	Ratnapur	
62	15	Banethok	Majhkot	
63	14	Banethok	Pelcachaur	
64	36	Pakawadi 1	Chhapa	
65	49	Banethok	Biruwa	
66	74	Daraun	PBM8	
67	82	Bichari Chautara	Aaruchaur	
68	40	Kuwakot	Chapakot	
69	9	Rangbhang	Biruwa	
70	12	Pelcachaur	Biruwa	
71	18	Manakamana	Biruwa	
72	25	Malayangkot	Ratnapur	
73	41	Chapakot	Ratnapur	
74	58	Neuwakharka	Pelakot	
75	71	Aaruchaur	Panchamul	
76	86	Jugley	Fulbari	
77	87	Fulbari	Bichari Chautara	
78	88	Jugley	Chilaunebash	
79	93	Wangshingh	Fulbari	
80	96	Kubhinde	Pawai Gaude	

Appendix L: Priority list of 'Dry weather links' to upgrades as 'All weathered road' in Syangja District of Nepal analysis from the new proposed methodology (without considering the critical population and distance)

Priority No	Link NO	From	TO	Remarsks
1	63	Triyasi	Sworek	Links important for the Network connection
2	68	Helu	Arjun Chaupari	
3	34	Tin Dobate1	Tin Doabte2	
4	60	Pelakot	Tindobate 3	
5	65	Bayarghari	Khilung Deurali	
6	77	Rangkhola	PBM10	
7	1	Syangja	Bahakot	
8	3	Bahakot	Oreste	
9	4	Oreste	Kitchanas	
10	64	Sworek	Kalikakot	
11	37	Galayang	Tulshi Bhayanjang	
12	66	Khilung Deurali	Dhapuk Shimal Bhayanjang	
13	13	Bayarghari	Banethok	
14	98	Pawai Gaude	Naya Bazar	
15	5	Kitchanas	Chisapani	
16	22	Jagat Bhayangjang	Malayangkot	
17	69	Arjun Chaupari	Rapakot	
18	20	Triyasi	Yaladi	
19	57	Galayang	Neuwakharka	
20	27	Jagat Bhayangjang	Kewore	
21	2	Bahakot	Kolma	
22	35	Tin Doabte2	Pakawadi 1	
23	76	PBM9	Syangja	
24	75	PBM8	PBM9	
25	79	PBM9	Phaparthum	
26	11	Bagalthok	Pelcachaur	
27	62	Thum Pokhara	Sirsekot	
28	24	Malayangkot	Shekham	
29	19	Triyasi	Majhkot	
30	16	Majhkot	Manakamana	
31	50	Oreste	Biruwa	
32	17	Manakamana	Chinnebas	
33	38	Tulshi Bhayanjang	Pakawadi 2	
34	70	Rapakot	Aaruchaur	
35	73	Daraun	Arjun Chaupari	
36	26	Malayangkot	Kyakmi	
37	54	Mirmi	Birgha	
38	72	Panchamul	Daraun	
39	80	Phaparthum	Chilaunebash	
40	55	Birgha	Aalamdevi	
41	90	Khadketari	Bhadkhola	
42	7	Chitrebhayang	Chinnebas	
43	81	Chilaunebash	Bichari Chautara	
44	95	Kubhinde	Aarukharka	
45	97	Pawai Gaude	Taksar	
46	28	Kewore	Chhapa	
47	30	Chhapa	Chapakot	

48	31	Chhapa	Ratnapur	
49	33	Ratnapur	Sakhar	
50	56	Aalamdevi	Chandi Bhayanjang	
51	29	Chhapa	Kuwakot	
52	91	Bhadkhola	Bange Fadke	
53	92	Bange Fadke	Wangshingh	
54	99	Naya Bazar	Thula Dihi	
55	59	Pelakot	Pidikhola	
56	78	PBM10	Arjun Chaupari	Links important for the Network performance
57	6	Chisapani	Chitrebhayang	
58	23	Malayangkot	Chinnebas	
59	10	Biruwa	Chinnebas	
60	36	Pakawadi 1	Chhapa	
61	32	Shekham	Ratnapur	
62	15	Banethok	Majhkot	
63	14	Banethok	Pelcachaur	
64	49	Banethok	Biruwa	
65	39	Pakawadi 2	Kuwakot	
66	74	Daraun	PBM8	
67	82	Bichari Chautara	Aaruchaur	
68	40	Kuwakot	Chapakot	
69	41	Chapakot	Ratnapur	
70	9	Rangbhang	Biruwa	
71	12	Pelcachaur	Biruwa	
72	18	Manakamana	Biruwa	
73	25	Malayangkot	Ratnapur	
74	58	Neuwakharka	Pelakot	
75	71	Aaruchaur	Panchamul	
76	86	Jugley	Fulbari	
77	87	Fulbari	Bichari Chautara	
78	88	Jugley	Chilaunebash	
79	93	Wangshingh	Fulbari	
80	96	Kubhinde	Pawai Gaude	