Vulnerability Scanning Methodologies Applied to Logistics Transportation Network

物流ネットワークにおける脆弱性評価手法の構築

By

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Summary

Logistics activities play one of the most important roles in society, especially economically. Transport is a fundamental part of logistics activities, which services a set of facilities in a logistics system. A reliable and efficient connection between each element of a logistics system is becoming increasingly important. However, transportation infrastructure networks are susceptible to threats from either human interference or natural disaster. “Threats” may be cyclical disruptions such as daily congestion and maintenance activities, or unexpected events such as traffic accidents, structural breakdowns, natural hazards, or even more rare events like terrorist attacks, to mention a few. Under these threats that may cause a logistics facilities failing or degrading severely, reliability and efficiency are difficult to be guaranteed in logistics transportation networks consisting of thousands of links and nodes and complex transit systems. The vulnerability of transportation networks under unexpected threats has been the subject of growing attention in recent years. However, network vulnerability assessment has been focused on passenger transport mode. Logistics transportation networks have not yet been treated as specific subjects even though their definitions of trip failure and degradation are different from passenger transport. What matters most for the logistics case is different from the passenger case. In freight transportation networks, the best case is similar to passenger transport networks, but trip failure is not limited to when there is no route between origin and destination. The objective of logistics transport is to get the right materials to the right place at the right time while optimizing the total operational costs of this process. Some detour or increase in cost may cause the product to be damaged or have excessive cost resulting in selling failure, which also means the logistics transport fails. Logistics transportation networks are more sensitive to time and cost compared to passenger transport. The methodology used to assess vulnerability of logistics transportation networks should be developed in a different way to passenger or other transport mode.

This study attempts to find a methodology to properly address the character of logistics transportation network vulnerability. In order to evaluate the performance of logistics transportation networks, time value is included in the generalized cost of logistics transportation. The generalized cost of logistics transport network is proposed considering both time value and transport cost. From

the logistics transport network user perspective, the generalized cost represents the trade-off between time consumption and travel cost because it includes both time value and cost. Moreover, network vulnerability assessment is impacted by the nature of the component degradation. The performance of logistics transportation networks is evaluated in different transportation facility degradation scenarios, including link and node degradation scenarios. The link degradation scenario is based on the assumption that the single link disrupt pattern from attacks by nature or human society only result in a single link disruption. However, the attacks are usually area covering and result in disruption to several nearby links. So the node vulnerability scanning is proposed to reflect this situation. The disruption of nodes representing intersection failure also involve failure of all links connected to it. In the logistics transportation system, this hypothesis can explain the situation when disasters such as snow storms and floods affect a transportation hub, causing failure of all connected links.

The concept of vulnerability analysis is related to evaluating the consequences of network degradation caused by incidents such as social or natural disasters. Many methodologies have been proposed to evaluate transportation network vulnerability by quantifying the consequence of partial network degradation. These vulnerability indices consider only the consequences of incidents but not their probability. However, while the consequences of network degradation can show how important these degraded parts are in the whole network operation, they cannot show which parts are vulnerable under a specific disaster. In practice, the probabilities of degradation between different parts, especially in large scale networks like inter-city logistics transportation networks, are quite different. Some components may have significant consequences in the event of degradation, but have very low probability of degradation occurring, so it may not be reasonable to say these parts are vulnerable to this disaster. There are different approaches for resisting different threats. For example, traffic control measures can be applied to reduce threats from daily traffic congestion, and structural measures can be taken to reinforce transportation networks to resist seismic disasters. If vulnerability is evaluated under specific disasters, the results would be helpful to take reinforcement measures to improve the network's ability to resist that disaster. In this study, the Seismic Vulnerability Index (SVI) is proposed to measure vulnerability of logistics transportation networks under seismic disasters. This

index considers both the difference caused by component degradation and also the probability of component degradation caused by seismic disaster. The consequence of network degradation is evaluated by the generalized cost of logistics transport. The probability of network degradation is determined according to the predicted probability of seismic hazards. It is supposed that transportation infrastructures will be destroyed at a certain earthquake intensity. Then the probability of transportation network degradation is determined using a predicted probability exceedance of seismic hazard, which shows the probability of seismic disaster over a specific intensity in certain years. A seismic vulnerability scanning methodology is developed to evaluate the vulnerability of logistics transportation networks under seismic disaster which is measured by the consequences of network degradation under a certain probability of degradation.

All these methodologies mentioned above are applied in study networks consisting of the Hokkaido logistics transportation network. This multiple logistics transportation network consists of express highway, national highway, prefecture arterial highway, railway, and maritime routes. On the other hand, the Hokkaido logistics transportation network is in an earthquake active region and destructive earthquakes have occurred regularly throughout history. Efficient vulnerability scanning algorithms are developed to make them applicable to transport networks including thousands of nodes and links. Finally the infrastructures of logistics transportation networks are classified into different vulnerable categories and visual results of are demonstrated using Geographic Information System (GIS) technology. The visualized vulnerability categories are useful for transportation network planners or maintenance agencies to detect the vulnerable spots of a transportation network and corresponding policies can be made to mitigate vulnerability under threats. The seismic vulnerability scanning will help to make reinforcement policy for logistics transportation networks to resist seismic damage.

This study aims to develop a vulnerability scanning methodology applicable to large scale logistics transportation networks such as intercity logistics transport networks. The results of the vulnerability scanning show how one single link or node degradation impacts the performance of the Hokkaido logistics transportation network, which is measured by generalized cost. The links and

nodes in categories with higher vulnerability index should have priority to keep in operation, otherwise there are great losses caused by degradation of these link and nodes. The seismic vulnerability evaluation results show the probable damage of the Hokkaido logistics transportation network caused by earthquake disasters. These results describe the vulnerability distribution in logistics transportation networks and provide assistance for making reinforcement policy to improve the reliability of transportation networks by reducing influence of potential threats. The research was undertaken to assist logistics managers, researchers and transportation planners to define and comprehend the basic views of vulnerability of logistics transportation networks and their various applications.

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CHAPTER 1 INTRODUCTION

1.1 Background

1.1.1 Transportation networks

Transportation is a movement of people, animals, or goods from one place to another. It plays a very important role in society development processes and it also evolves along with this development. Transportation systems include spatial connections, vehicles and operations. The history of transportation is largely one of technological innovations. Advances in technology have allowed people to travel further, explore more territory, and expand their influence over larger and larger areas. Even in ancient times, tools such as foot coverings, skis, and snowshoes lengthened possible travel distances. The history of transportation is simultaneously a history of technology change, population movement, colonialism, economic growth and business development. Transportation is a robust causal mechanism that mediates many important social processes and outcomes. Its causal effectiveness is fairly transparent: new transportation opportunities create new options for social actors, who take advantage of these opportunities in choosing a place to live and work, in pursuing political goals, in moving armies, and in generating income. So transportation is a causal mechanism whose foundations are especially visible, and whose causal consequences are often very large.

As new inventions and discoveries were applied to transportation problems, travel time decreased while the ability to move more and larger loads increased. The history of road involves the development of new vehicles such as animal-drawn vehicles, bicycles, motor cars, motor trucks and electric vehicles. Earth tracks were created when humans needed to carry goods from one point to another, and these tracks were naturally created at points of high traffic density. With the growth of trade, tracks were often flattened or widened to accommodate animal traffic. In the Industrial Revolution, John Loudon McAdam designed the first modern highways, using inexpensive paving material of soil and stone aggregate, and he embanked roads a few feet higher than the surrounding terrain to cause water to drain away from the surface (Lay, 1992). With the development of motor

transport there was an increased need for hard-topped roads to reduce washaways, bogging and dust on both urban and rural roads, originally using cobblestones and wooden paving in major western cities. In the early 20th century macadam and concrete paving were extended into the countryside, forming the shape of the modern road network.

Maritime history also deals with the development of navigation, oceanography, cartography and hydrography. Dating back to the stone ages, primitive boats were developed to permit navigation of rivers and for fishing in rivers and off the coast. With the development of civilization, bigger vessels were developed both for trade and war. In the Mediterranean, galleys were developed about 3000 BC, which were eventually rendered obsolete by ocean going sailing ships. During the Industrial Revolution, the first steamboats and later diesel powered ships were developed, meanwhile specialised craft were developed for river and canal transport. Canals were developed in Mesopotamia about 4000 BC (Paine, 2014). The maritime history has developed from the age of navigation, age of discovery, age of steam, to the 20th century and 21st century. Maritime history has been tied closely with civilization development. For centuries the size of a country's merchant marine and the extent of its docklands were symbols of national prestige. Now in the modern maritime industries, ships and ports are owned by multinational companies and they have been one of the most important drivers of globalisation, exerting a powerful influence on our lives.

In the 20th century, aviation brought a new era of transportation. Much of the focus of early research on aviation was on imitating birds, but through trial and error, balloons, airships, gliders and eventually powered aircraft and other types of flying machines were invented. During World War II, there was a drastic increase in the pace of aircraft development and production. All countries involved in the war stepped up development and production of aircraft and flight based weapon delivery systems, such as the first long range bomber. The technologies developed in the war came to form a good basis for commercial aviation, which grew rapidly after the war, using mostly ex-military aircraft to transport people and cargo. Nowadays, aviation has become an important part in people's travel. While air traffic demand has increased as economies have grown, air transportation itself can be a key facilitator of economic growth. Not only is the aviation industry a major industry in its own

right, employing large numbers of highly skilled workers, but more importantly it is an essential input into the rapidly growing global economy. Greater connections to the global air transport network can boost the productivity and growth of economies by providing better access to markets, enhancing links within and between businesses and providing greater access to resources and to international capital markets.

Innovation continues today. The development of transportation modes has contributed much to people's mobility, reducing travel cost, and increasing efficiency. The modern transportation systems allow people to travel all over the world in short time by transit between different transportation modes. The worldwide travel distances need large scale spatially covering transportation networks to provide physical infrastructure, and high travel efficiency needs accurate and reliable transport operation systems. Every section in modern transportation systems will impact the performance of the whole network, however, it is impossible to guarantee that every individual section is not exposed to treats in a complex transportation network. Additionally, there are more and more threats from both human society and the natural environment that could potentially disrupt transportation networks.

1.1.2 Threats to transportation systems

The disruptions of transportation systems caused by unscheduled events, especially earthquakes, have sudden and significant impacts not only on the region where the event occurs but also on other regions which are connected by transportation networks. Transportation infrastructure damage in these earthquakes caused substantial disruption and loss to the regional economies. Recent earthquake disasters have repeatedly demonstrated the seismic vulnerability of transportation systems. In the Kobe, Japan, earthquake in January 17, 1995, the damage to highways and subways was the most graphic image of the earthquake, and images of the collapsed elevated Hanshin Expressway made front pages of newspapers worldwide. Most people in Japan believed those structures to be relatively safe from earthquake damage because of the steel reinforced concrete design. However, Hanshin Expressway Route 43 in three locations in Kobe and Nishinomiya were knocked over, blocking a link that carried forty percent of Osaka-Kobe road traffic. Half of the elevated

expressway's piers were damaged in some way, and the entire route was not reopened until September 30, 1996. Three bridges on Route 2 were damaged, and it was reopened well ahead of Route 43 and served as one of the main intercity road links for a time. Many surface highways were clogged for some time due to the collapse of higher capacity elevated highways. Most railways in the region were also damaged in the earthquake. In the aftermath of the earthquake, only 30% of the Osaka-Kobe railway tracks were operational. Kobe Port was heavily damaged due to liquefaction. Damage to expressways and railway lines in Kobe disrupted efforts to transport relief supplies to quake victims. The 1995 Kobe Earthquake caused disastrous damage to the port of Kobe, which includes direct repair costs of $5.5 billion and an estimated economic loss of $6 billion (Werner, Dickenson, & Taylor, 1997). The aftermath of the 1995 earthquake saw traffic flows in the port of Kobe redirected to nearby hub ports such as Busan, Shanghai and Kaohsiung, some of which never returned even long after the cargo handling capacity was restored (Fujita & Hamaguchi, 2012). On January 17, 1994, the Northridge earthquake in California destroyed structures on four important freeways in the Los Angeles basin. Wesemann et al. employed a financial incentive about this disruption. They conducted as part of the comprehensive transportation recovery evaluation justified those bonus clauses and indicated that the quantifiable transportation related costs associated with the travel disruption and delay on the four damaged routes combined in the Los Angeles basin exceeded $1.6 million per day (Wesemann, Hamilton, Tabaie, & Bare, 1996). Highway bridge failures occurred in the 1989 Loma Prieta event that struck the San Francisco Bay Area. More recently, the Great East Japan Earthquake and Tsunami on March 11, 2011, disrupted a significant part of communications infrastructures both within the country and in connectivity to the rest of the world. Tokyo is the capital city of Japan around and it received limited physical damages form this earthquake. However, immediately after the main earthquake, all public transportation in Tokyo, including trains and subways, was stopped. Highways and airports were closed. By evening, roads were filled with people walking home, and cars were completely stuck on the roads.

In addition to earthquake, the disruptions to transportation infrastructure system are also from other natural disasters such as flood, tsunami, volcano eruption, snow storm, sea level elevation

caused by climate change and so on. Comparing to low possibility nature disasters disruption, there are also threats from human to transportation infrastructure system with much higher possibility to happen. Terrorist attacks became to a serious threats recent years, which are only threats to human safety but also to transportation system disruption whose failure will result in huge economic loss reducing defence capability. Daily disruptions such traffic accidents and traffic congestion will also cause transportation network partially degraded. The collapse, on August 1, 2007, of the I-35W Bridge over the Mississippi River in Minneapolis, abruptly interrupted the usual route of about 140,000 daily vehicle trips and substantially disturbed the flow pattern of the network (Zhu & Levinson, 2012). In addition to the heavy losses in life and injury, the network disruption also significantly impacted road network users and reshaped travel patterns, which generated significant cost due to longer travel distance, higher levels of congestion, and the resulting opportunity losses. According to Minnesota Department of Transportation, rerouting alone caused by the I-35W Bridge collapse could cost individual travellers and commercial vehicles $400,000 daily. Xie and Levinson (Xie & Levinson, 2011) find a lower, but still large, estimate of expected costs to road users, between $71,000 and $220,000 a day depending on how flexible road network users in the system adjusted their trip destinations in response to the bridge closing. As a result, a significant financial incentive was given to the contractor for the early completion of the replacement bridge. The collapse, in 1975, of Tasman Bridge in Hobart, Australia, significantly disrupted the transportation network because the nearest alternative, the Bridgewater Bridge, required 50 kilometres extra drive and there was little vehicular ferry service available. During the 14 months of reconstruction, of the 44,000 daily trips before the bridge collapse, 60% disappeared (Hunt, Brownlee, & Stefan, 2002). Understanding the vulnerability of transportation network under these threats are strategically important for society safety and economic development.

Special events such as Olympic Games also significantly disrupt normal traffic by introducing a highly concentrated travel demand. For example, high public transport ridership was also observed during the 2000 Sydney Olympics according to (Hensher & Brewer, 2002) although bus riders had to wait as long as 45 minutes. As a result, background traffic dropped 2% to 4.5% depending on the

location, and travel speed doubled. These events show great potential for public transit. Seaports are susceptible to a variety of risk sources, and the resultant disruptions can have significant detrimental effects on supply chains. The shutdown of Los Angeles-Long Beach Ports in 2002 results in a backlog of cargos and vessels for months and an average export loss of $20 million per day for the US economy (Park, Gordon, II, James, & Richardson, 2008). Even though no major terrorism activities have been reported in shipping and ports, the susceptibility of such sophisticated supply chain nodes to terrorist attacks and the catastrophic potential is widely acknowledged in the literature (Paul & Maloni, 2010; Pinto & Talley, 2006).

Transportation networks are the backbone of modern society which play very important roles in economy development and human daily life. The modern transportation networks become more and more multiple and complex as technologies develop. The networks usually consist of thousands of road sections and intersections covering towns, cities, states, nations or even inter-nations. The transportation systems include not only one transport mode such as private car, bus, train, ship, air plane and so on. Various transport modes are connected by transit systems and shape the modern complex transportation networks. Reliability of transportation network is more and more important for the operation of transportation networks as it is more complex. Disruption to any part of transportation networks will result in performance degradation of the whole network as a complex system. Threats to transportation systems may cause the road network to fail or to become severely impeded. There are accidental but destructive threats such as an array of natural hazards, structural breakdowns, power failures; daily but recoverable disruptions such as traffic accidents, congestion, to mention but a few. Consequently, weakness and vulnerable spots of the transportation network need to be addressed under disruptions from these threats.

Vulnerability assessment of a network is becoming a major concern in many fields. It is a process to identify, quantify, or prioritize the vulnerability in a system. It has been performed to, but not limited to, information system, communication network, energy network, water system, and transportation network. Vulnerability assessments may be conducted on behalf of a range of different organizations, from small businesses up to large regional infrastructures. Vulnerability is from the

perspective of disaster management assessing the threats from potential hazards to the population and to infrastructure. It can be conducted in the political, social, economic or environmental fields. The vulnerability of transportation networks entered into the research area since some 10 years ago, sparked primarily by the earthquake in Kobe in 1995, and more recently, the events of September 11th, 2001, when the threat of terrorist attacks became the hotbed of vulnerability research. Perceptions of risks and threats to infrastructure are from both natural disasters and from human malevolence. To mitigate those risks in transportations systems, one practical way is to identify critical locations in infrastructure networks, whose failure will have significant impacts to the performance of the entire network, and corresponding reinforce measurements are conducted to the infrastructures of transportation networks. However, the road transport network is large, wide and diverse in nature. A proper measurement should be developed to assess impacts of interruptions and a good model should be built to represent how the networks are interrupted. Thus there are needs for the development of vulnerability assessment for transportation network.

1.2 Objectives of study

The importance of logistics management has been growing in various areas, due to the trend of globalization in recent decades. Transport is a fundamental part of logistics activities which play a critical role in society development. Transportation is required throughout the whole production process, from manufacturing to delivery to the final consumers, as well as returns, which influences the performance of logistics system greatly. Only good coordination between each component would bring optimal benefits. While a global logistics network enables companies to leverage lower cost manufacturing, there are significant challenges imposed on transportation managers in ensuring products delivered over long distances arrive on time and are distributed to the right locations. Transportation costs are a major contributor to overall logistics product costs. Better transportation management helps companies improve their overall logistics efficiency. The longer lead times with global suppliers, volatile fuel prices and risks such as unavoidable delays, make estimating the cost and time associated with transportation difficult. Uncertainty in transportation often leads to higher inventory costs as companies buffer their stock. The safety and reliability of transportation networks

significantly impact logistics industries. To reduce costs caused by transportation uncertainty and ensure that the right product reaches the right location on time, it is important to find the vulnerable spots in the logistics transportation network. With industrial specialization and refinement and development of our society, reliable and efficient connection between each element of logistics systems is becoming increasingly important. Thousands of links and nodes and complex transit systems mean that reliability and efficiency are difficult to guarantee under threats that may cause logistics facilities to fail or degrade severely.

The vulnerability of transportation networks under unexpected threats has been the subject of growing attention in recent years. However, among present research about vulnerability assessment, logistics transportation networks have not yet been treated as specific subjects even though their definitions of trip failure and degradation are different from passenger transport. What matters most for the logistics case is different from the passenger case. In freight transportation networks, the best case is similar to passenger transport networks, but trip failure is not limited to when there is no route between origin and destination. The objective of logistics transport is to get the right materials to the right place at the right time while optimizing the total operational costs of this process (Tseng, Yue, & Taylor, 2005). Some detour or increase in cost may cause the product to be damaged or have excessive cost resulting in selling failure, which also means the logistics transport fails. Logistics transportation networks are more sensitive to time and cost compared to passenger transport (Fowkes, Firmin, Tweddle, & Whiteing, 2004). The methodology used to assess vulnerability of logistics transportation networks should be developed in a different way to passenger or other transport mode. This study proposes a methodology applicable in logistics transportation network vulnerability assessment. In order to evaluate the performance of logistics transportation networks, logistics value is included in the generalized cost of logistics transportation.

Most researchers evaluate vulnerability by quantifying the consequences of partial network degradation. Parts of a transportation network such as links and nodes are supposed degraded by any attack from either human interference or natural disaster. “Attacks” may be cyclical disruptions such as daily congestion and maintenance activities, or unexpected events such as traffic accidents,

structural breakdowns, natural hazards, or even more rare events like terrorist attacks, to mention a few. It is difficult to predict the probability of these threats occurring and which part of the network will be affected. Therefore, most vulnerability indices consider only the consequences of incidents but not their probability. However, while the consequences of network degradation can show how important these degraded parts are in the whole network operation, they cannot show which parts are vulnerable under a specific disaster. In practice, the probabilities of degradation between different parts, especially in large scale networks like inter-city logistics transportation networks, are quite different. Some components may have significant consequences in the event of degradation, but have very low probability of degradation occurring, so it would not be reasonable to say these parts are vulnerable. There are different approaches for resisting different threats. For example, traffic control measures can be applied to reduce threats from daily traffic congestion, and structural measures can be taken to reinforce transportation networks to resist seismic disasters. If vulnerability is evaluated under specific disasters, the results would be helpful to take reinforcement measures to improve the network's ability to resist that disaster.

Moreover, network vulnerability assessment is impacted by the nature of the component degradation. The performance of logistics transportation networks should be evaluated according to transportation facility degradation scenarios. Many researchers have proposed vulnerability assessment based on link degradation of transportation networks, while others (Jenelius & Mattsson, 2012) present approaches to systematically analyse the vulnerability of road networks under disruptions covering extended areas representing failures caused by events including floods, heavy snowfall, storms, wildfires, and so on. The degradation patterns should be part of transportation system vulnerability research. This study proposes vulnerability scanning algorithms in both link and node degradation scenarios. Additionally, the modern transportation networks consist of multiple transport modes including roads, railways, marine lines, and airlines spanning cities, and even nations. Traffic simulation in complex transportation networks consisting of thousands of links and nodes will be a challenge for current computational technologies. Efficient traffic models in vulnerability scanning should be applied in large-scale transportation networks. In order to reduce computational

demands, an efficient vulnerability scanning algorithm will be developed to make this methodology feasible in large scale networks. The research was undertaken to assist logistics managers, researchers and transportation planners to define and comprehend the basic views of vulnerability of logistics transportation networks and their various applications.

The objectives of this study are summarized as following:

- Develop models to evaluate performance of logistics transportation networks. Compared with passenger transportation, logistics has specific definitions of transport trips and different requirements of transportation network performance.
- Develop models to do vulnerability scanning in multiple logistics transportation networks. Vulnerability scanning in a complex transportation network that includes thousands of links and nodes is quite computationally demanding, so efficient models have to be developed to be applied in large scale transportation networks.
- Consider multiple transport modes in logistics systems. The modern logistics systems are worldwide and have not only one single transport mode. Cargos are usually transported in multiple transportation systems including highway roads, maritime, and aviation.
- Scan vulnerability based on different degradation scenarios. Transportation networks will degrade in different patterns by different threats. Vulnerability scanning under different degradation scenarios will show vulnerable characteristics of the network and the results will be helpful in making resistance policy to specific threats.
- Apply methodologies to study networks. Practical methodologies are the foundation of engineering research. Application to a real logistics transportation network is helpful to look into details of this study and make policy recommendations.

1.3 Dissertation overview

This dissertation is organized into six chapters and a bibliography. The content of each chapter is summarized as follows.

Chapter 1 presents the introduction of this study including background, research objectives, and dissertation overview. The background section explains what transportation networks consist of, how they are involved in development of the economy and daily human life, what features different transport modes have. It also shows how severe threats make existing transportation network vulnerable and the necessity of vulnerability evaluation. Research objectives show the results of this study are expected and the aims of this research.

Chapter 2 presents the literature review of vulnerability related research, intermodal freight transport system, time value in freight transportation. Vulnerability related research section enumerates related research to network vulnerability evaluation. Intermodal freight transport system explains models of the intermodal freight which will be studied in the following chapters. Time value in freight transportation section illustrate the conception of time value in logistics transportation systems.

Chapter 3 describes the methodologies proposed in this study, including sections of generalized cost of logistics transport network, total generalized cost in logistics transport network, shortest path problem, and vulnerability scanning of logistics transport network. Generalized cost of logistics transport network section states the definition of generalized cost in logistics transport models. Total generalized cost in logistics transport network section explains the total generalized cost as the measurement of logistics transportation network performance. Shortest path problem section illustrates the models applied in transportation simulation. Vulnerability scanning of logistics transport network section show the algorithm to evaluate vulnerability of large scale and complex network.

Chapter 4 applies the methodology proposed in Chapter 3 into a multiple logistics transportation network, and analyses the results. This chapter is a case study of vulnerability scanning in multiple logistics transportation networks which is conducted both in link and node degradation scenarios.

Chapter 5 doses research about the seismic vulnerability which estimating transportation network vulnerability under seismic disasters. This chapter is a case study of seismic vulnerability assessment of logistics transportation networks. In this case, not only the consequence of network degradation is considered but also the probability of the degradation.

Chapter 6 concludes the results of this study and possible application to practice. This chapter also illustrates the contribution of this study to transportation planning and logistics industry research.

CHAPTER 2 LITERATURE REVIEW

2.1 Logistics transportation systems

2.1.1 Definition of logistics

The increasing logistics flows have been a fundamental component of contemporary changes in economic systems at the global, regional and local scales. The logistics activities involves the movement of physical goods from one location to another. The definitions pf logistics has received much attention from the military during both World Wars. The Second World War necessitated greater movement of troops and supplies than any other period in history. Luttwak described logistics as all the activities and methods connected with the supply of armed force organizations, including storage requirement, transport and distribution (Luttwak, 1971). The aim of logistics is to provide each echelon of armed force organization with the optimum quantity of each supply item, in order to minimize both overstocking which restricts mobility and causes diseconomies and shortages of essential equipment (Luttwak, 1971). Over the time, the application of logistics has moved into the business area. Logistics has been defined both in the military and business contexts. In an industrial context, the art and science of obtaining, producing, and distribution material and product in the proper place and in proper quantities. In a military sense, its meaning ca also include the movement of personnel (Cox, Blackstone, & Spencer, 1995). Cavinato defines the logistics in a true business context. The management of all inbound and outbound materials, parts, supplies, and finished goods. Logistics consists of the intergrade management of purchasing, transportation, and storage on a functional basis (Cavinato, 1982). This definition expands logistics beyond merely physical distribution by including both incoming and outgoing materials. There are also definitions from professional organizations. Council of Logistics Management defines logistics as: the process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services and related information from the point of origin to the point of consumption for the purpose of conforming to customer requirements (Council of Logistics Management, 1998). This definition includes inbound, outbound, internal and external movements, and return of materials for

environmental purposes. Logistics is defined by Japan Institute of Logistics Systems (JILS) as: logistics is the management which synchronizes such providing actions as procurement, production, sales, and distribution with demands. It aims to enhance corporate competitiveness and increase corporate value by realizing fulfilment of customers' satisfaction, cutback of unprofitable inventory and minimization of its transfer, and reduction of supply costs (Japan Institute of Logistics Systems, 2006).

2.1.2 Intermodal logistics transportation system

From the definitions of logistics above, the movement of goods is critical part of logistics system. The exchange of goods is a constant feature of human economic activity. It was once essential for the rise of the mercantile economy in medieval Europe and became a large scale activity during the industrial revolution (Braudel, 1982). Although logistics were initially applied to military operations, its most significant impact goes through the functions of production, distribution and consumption. The location of industrial activity and also the geography of manufacturing in general evolved with respect to accessibility improvements that were particularly offered by transportation in logistics systems. Vice versa, every progress during the process of industrialization embodies distinct transportation orientations and appropriate infrastructure requirements (Hayter, 1997). This was true for the railroad in the fordism economy, as it is for trucking and air freight more recently. Mass distribution and marketing became part of modern management and have been important factors of development of economy. The organization and technology of modern distribution are embedded in a changing macro to micro economic framework. Contemporary production and distribution is no longer subject to single firm activity, but increasingly practiced in networks of suppliers and subcontractors (Dicken & Thrift, 1992).

The extended range of suppliers and the globalization of markets have brought increasing pressures on transportation of logistics. An integrated freight transport system requires a high level of coordination. Intermodal freight transport has developed into a significant sector of the logistics transportation. This development has been followed by an increase in multiple freight transportation research. Intermodal transport is a complex system and has characteristics which distinguishes it from

other transport systems. Intermodal logistics transport is the movement of goods in one and the same loading unit or vehicle by successive modes of transport without handling of the goods themselves when changing modes (European Conference of Ministers of Transport, 1997). In transport practice, intermodal transport is considered as a competing mode and can be used as an alternative to unique modal transport. In the 1980s and 1990s, intermodal logistics transportation general has become an important policy issue and the related policy has been strongly advocated because of environmental concerns, reasons of overall efficiency and the benefits of coordination of modes to cope with growing transport flows (OECD, 2000).

Analysis of a given intermodal logistics transport network requires an understanding of the network size, of the intensity of operations, of the technology in use, and individual components of the systems. Usually networks are assumed of equivalent size in terms of the spatial coverage, number of nodes and the volumes of demand they serve. Network nodes represent the origins and destinations of goods. They also represent clustering of manufacturing plants, warehouses, logistics centres and freight terminals located in shipper and receiver areas. Intermodal terminals are also nodes but only for the short term storage or direct transferring of goods. Goods flows in any network are consolidated to be by standardized units containers, swap bodies and semitrailers. Transport infrastructure provides the means for movement of the freight units. The nature of this infrastructure and the quality of service it offers depends on the volume of demand, the efficiency and effectiveness of the services, and the physical scale of the hardware.

Intermodal transport can be described as the following of steps (European Commisson 2000, 2000):

(1) Collection goods in the originating zone and transportation by truck to the origin intermodal terminal located in the shipper area;

(2) Transhipment at the origin intermodal terminal from truck to the trunk-haul, non-road transport mode such as rail, inland waterways, and air;

(3) Line-haul transportation between the origin and destination intermodal terminals by the trunk-haul mode;

(4) Transhipment at the destination intermodal terminal in the receiver area from the trunk-haul mode to trucks;

(5) Distribution from the destination intermodal terminal to the destination zone by truck.

There are internal and external costs associated with a movement through an intermodal logistics transport system. Internal costs comprise the operators' costs of moving units between shippers and receivers (Janic, 2007). The external costs are costs that networks impose on society, including environmental costs. Both categories of cost can be specified for each stage in the networks. They generally depend on the network nature, characterised by its location, distances and number of nodes; the intensity of activities in the network characterised its use; the efficiency of services, and the prices of inputs. Particularly relevant for external costs are the emission rates of pollutants and the number of accidents, and their impacts on society and the environment. In addition, network services can impose delays on other traffic by creating congestion.

Florian and Crainic developed STAN (Strategic Planning of National and Regional Freight Transportation), modelling and planning software that uses a proprietary, multimodal network model of highway, rail, and water links(Guelat, Florian, & Crainic, 1990). Cost assignment can be performed using STAN, in a similar fashion to the methods used in this study, where costs can be calculated using algebraic formulas, which can then be applied to particular links within the network. The network optimization model that is used to simulate network flows in STAN is a nonlinear multimode-multiproduct assignment formulation that minimizes the total generalized system cost. The generalized cost is computed for each link and transfer of the network, as a weighted sum of an operating cost function, a delay function and an energy consumption function (Lubis, Prasetyo, & Samuel, 2003). Russ et al examined the freight network in Indonesia to determine route assignment patterns in order to create a planning model for determining the locations of future expressway projects(Russ, Yamada, Castro, & Yasukawa, 2005). Yamada et al examined the transport network

within the Philippines, where there is a need to develop a comprehensive multimodal freight network, and used the Genetic Local Search optimization algorithm to determine the optimal locations for multimodal freight development and expansion within the country(Yamada, Russ, Castro, & Taniguchi, 2009).

Another example of a multimodal network model used in international studies is NODUS. NODUS is a geographic information system, developed at the University of Mons (Belgium), and has been used to model freight movement in European countries using the European freight network. NODUS is typically used in studies involving multimodal freight flows and freight mode determination. "NODUS encompasses the concept of 'generalized cost' which allows for the integration of all factors relevant to transport decision making in terms of monetary units. The virtual network requires the development of four types of cost functions, which are associated with specific virtual links: loading/unloading, transit, transhipping, and moving virtual links"(Geerts, Jourquin, SA, & LUC, 2001). Another network model used in similar freight studies is the SMILE (Strategic Model for Integrated Logistics and Evaluation) network model, developed by the Institute for Road Safety Research, in the Netherlands (1996). This model can be used as a tool to predict future development, using Economy and Transport modules for the purpose of forecasting. A "chain structure" is used to depict supply chain between origin and destination travel. The model can then be evaluated to determine if the predicted development has an impact on freight travel and the freight network (Wilson, 2004).The Oak Ridge National Laboratory's multi-modal freight network contains highway, rail, air, and waterway links. Each link contains information necessary for estimating freight flows. Notional links are established in the network to route vehicles to desired destinations. Nodes represent access points and locations of terminals where transfers within and between modes take place.

2.1.3 Transportation cost in logistics system

Traditionally transports costs were considered as a distance decay function. The most significant considerations of logistics on transport costs are related to the functions of composition, transhipment and decomposition, which have been transformed by logistics. More specifically, composition and decomposition costs, which involve activities such as packaging, warehousing, and

assembly of goods into batches, can account to 10% of production costs. A higher level of inventory management can lead to significant reduction in the logistical friction as well as terminal improvements decreasing trans-shipment times and costs. Time is becoming as important as distance in the assessment of transportation costs and impedance. As transport costs went down through space or time convergence, the value of time went up proportionally. For instance, between 1950 and 1998, the average time in transit for imported goods fell from 40 days to about 10 days. Each transit day adds about 0.8% to the final cost of goods. As such, 20 days at sea adds the equivalent to a 16% tariff on international trade (Hummels & Schaur, 2012). Concomitantly, the costs of logistics in the American economy went from about 16% of the GDP in 1980 to 10% in 2000 (Hesse & Rodrigue, 2004). Within the components of logistics costs, the portion of transportation segment has as well as increase for 46.5% of total logistics costs in 1980, to 58.6% in 2000 as shown in Figure 1 (Hesse & Rodrigue, 2004). Inventories are thus increasingly in circulation and inventory costs were reduced proportionally. The issue of mobile inventories, as opposed to the traditional concept of fixed inventories has blurred the assessment of logistics costs. Trade-offs between fixed costs such as inventories and warehouses and variable costs, transportation, play a major role in corporate strategies, because the advancement of new technologies allows for the mobilization of inventories, subsequently, the elimination of facilities, whereas the deregulation of transport markets attracted firms to expand their shipping and transportation activities, by significantly lowering the freight rates. Thus companies were able to reduce a considerable amount of total distribution costs.

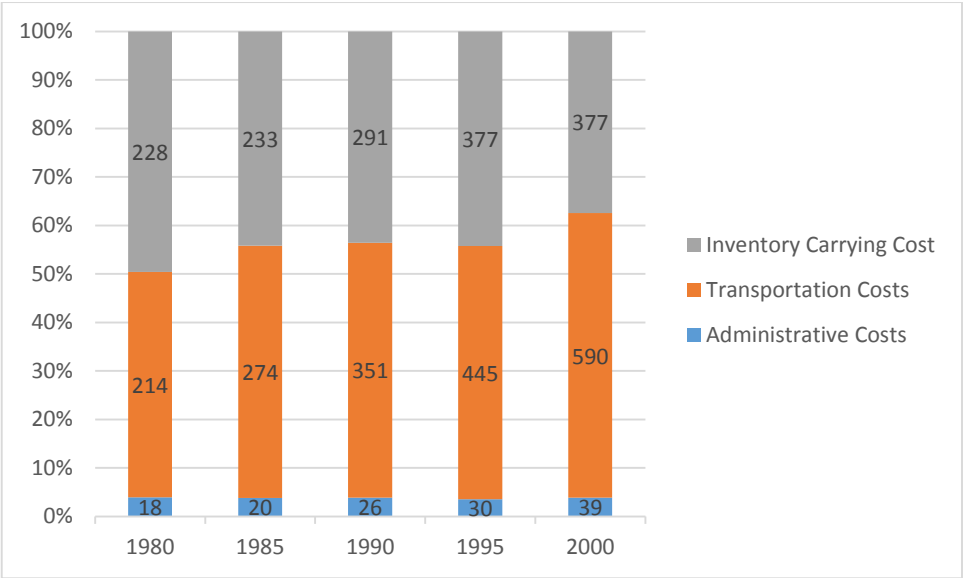

Figure 1 Logistics costs, US, 1980–2000 (billion US Dollar) (source: Hesse & Rodrigue, 2004)

2.1.4 Time value in logistics transportation

Private carriers are the providers of freight services, and they must earn a profit. Carriers usually follow a schedule and often need to deliver goods to receivers by a specific time. Meanwhile, carriers try to minimize shipping costs by carefully selecting routes, departure times, and equipment. Values of time are particularly important because they arise in the evaluation of many policies. As an example, time values are usually used as one component of the measurement of total economic benefits from alternative highway improvement projects. In addition, some studies adopt time value to estimate the effects on vehicles of proposed tolls, new highway connections, highway widening, or lane use policies that affect peak period capacity. Mei uses a policy sensitive truck cost model to test on a full scale simulation. A detailed cost model of trucking was developed by the research team for the purposes of policy analysis. This cost model followed industry practice by basing most cost components on the length of haul, which would imply that truckers would mostly minimize distance when choosing routes (Mei, Hussein, & Horowitz, 2013).

Smalkoski evaluates time values of commercial vehicle operators in Minnesota. The value of time for commercial vehicle operators in Minnesota is part of a larger investigation of the costs and benefits of the spring load restriction policy in Minnesota also known as seasonal load restrictions (SLR). The cost of SLR on commercial vehicle operators is assumed to be the consequence of

alternate behaviour resulting from the imposition of the restrictions. This alternate behaviour can combine any of the following options: shift the seasonal timing of shipments, reduce load size per vehicle, change vehicle type, or change routes(Smalkoski & Levinson, 2008).

2.2 Vulnerability related research

While not necessarily as congested as urban transportation network, the economic consequences of even a relatively short-term disruption in travel on rural links may be extremely serious for these regions, effectively cutting or severely curtailing access to other regions of the country, and even isolating the affected region from particular inputs or markets. One of several dramatic consequences of the Northridge earthquake was the damage to several major freeways and arterials. Some transport related impacts were longer lasting because they were affected by other factors; for example, extensive damage to the mall nearest to Northridge earthquake affected shopping behaviour for more than a year (Gordon, Richardson, & Davis, 1998). In 2004, a tanker truck accident along I-95 closed a mile long section of interstate near Bridgeport, Connecticut of U. S. A.. The economic consequences of the closure were severe, with construction costs alone amounting to $4 million and another $11 million in emergency federal aid required to reopen the interstate (Scarponi, 2004). The impact of this closure on the network was not only a function of the demand on the closed section itself, but also on the availability of alternative detour routes, their capacity and level of usage.

The blockage or degradation of one or more network links, particularly those that are heavily travelled, could have direct and serious economic consequences in terms of overall system travel time and cost increases, but also with respect to freight logistics management (M. G. Bell, 2000; Chen, Yang, Lo, & Tang, 2002; Smith, Qin, & Venkatanarayana, 2003). Not only could supply routes and delivery schedules be disrupted, but also the costs associated with rescheduling and rerouting could be prohibitive for both suppliers and resellers. Rerouting traffic could also result in additional safety risks and congestion on alternate interstate segments, particularly if a large volume of commercial vehicle traffic were routed to links that were already operating at or close to capacity. Depending on the spatial layout of the network such as network topology and on specific origins and destinations,

different types of traffic could have very difficult times rerouting in the event of a link failure (M. G. Bell, 2000).

Transportation network vulnerability has received increasing attention in recent years as threat levels increases. However, even the definition of vulnerability has not yet been clearly identified. It is still confused with reliability, risk, accessibility and so on even if some researchers have tried to untangle these relationships.

2.2.1 Reliability

The economy depends on heavily on an efficient and reliable transportation system to provide accessibility and promote the safe and efficient movement of people and goods. The transportation system has been identified as the most important lifeline in the event of natural disasters such as earthquakes, floods, hurricanes, and others. Recovery of other lifelines such as water supply, electrical power system, sewer system, communication, and many others depends strongly on the ability to transport people and equipment to damaged sites. Bell defines transportation network reliability as "A network is reliable if the expected trip costs are acceptable even when users are extremely pessimistic about the state of the network" (M. G. Bell, 2000). He points out that reliability has two dimensions: network connectivity and performance reliability. According to Bell, reliability pertains directly to instances of natural disaster when parts of the transportation network may fail and also to road space reallocation among competing transportation modes such as transit, pedestrians and cars. In the case of network connectivity, the more sparsely connected the network, the more difficult it may be for travellers to arrive at their destinations on schedule if there are segment blockages or failures. Measuring reliability is difficult as it includes both the physical infrastructure and the behavioural responses of travellers. The literature reviews of reliability of transportation network are divided in to reliability of connectivity and performance reliability.

2.2.1.1 Reliability of connectivity

Connectivity reliability is concerned with the probability that the network nodes remain connected. A special case of the connectivity reliability is the terminal reliability, which concerns the

existence of a path between a specific origin–destination (OD) pair (Iida & Wakabayashi, 1989). For each node pair, the network is considered successful if at least one path is operational. A path consists of a set of components such as road section, which are characterized by zero-one variable denoting the state of each arc when it is in operating or failure. Capacity constraints on the arcs are not considered when finding the connectivity reliability. This type of connectivity reliability analysis may be suitable for emergency connectivity, such as rescue connectivity after earthquakes, but there is an inherent deficiency in the sense that it only allows for emergency operating states without taking in the travel cost and travel demand. Additionally, this approach only allows for two operating states: operating at full capacity or complete failure with zero capacity. This binary state approach prevents the application to everyday situations where arcs are operating between these two extremes. Thus, transportation network reliability and risk assessment results obtained through this approach may be misleading.

2.2.1.2 Performance reliability

Another measure of network reliability is travel time reliability or the coefficient of variation of travel time (Yasuo Asakura & Kashiwadani, 1991). This is concerned with the probability that a trip between a given origin and destination pair can be made successful within a specified interval of time. This measure is useful to evaluate network performance under normal daily flow variations. Bell et al. proposed a sensitivity analysis based procedure to estimate the variance of travel time arising from daily demand fluctuations (M. Bell, Cassir, Iida, & Lam, 1999). Asakura extended the travel time reliability to consider capacity degradation due to deteriorated roads (Y Asakura, 1999). He defined travel time reliability as a function of the ratio of travel times under the degraded and non-degraded states. This type of reliability can be used as a criterion to define the level of service that should be maintained despite the deterioration of certain links in the network. When the ratio is close to unity, it is essentially operating at ideal capacity; whereas when it approaches infinity, the destination is not reachable because certain links are so severely degraded. This extreme case is consistent with network connectivity reliability. Bell uses a game theory approach to evaluate the performance reliability of a transportation network (M. G. Bell, 2000). Chen et al. define capacity

reliability as a network performance index: “the probability that the network can accommodate certain traffic demand at a required service level, while accounting for drivers’ route choice behaviour”(Chen et al., 2002).

2.2.2 Flexibility

Flexibility is the ability to accommodate, withstand or handle uncertainty (Chen & Kasikitwiwat, 2011). It describes the level of capability a system can handle or absorb uncertainties or changes. In systems engineering, flexibility is the characteristic of the interface between a system and its external environment(Corrêa, 1994). It has been widely researched in the field of manufacturing. Many categories, such as machine flexibility, operation flexibility, and process flexibility, have been adopted as key strategies for improving market responsiveness in uncertain demand. The typical reason that manufacturing industries have adopted flexibility is to speed up the entire product cycles. In transportation, flexibility is one of the important performance measures needed to deal with demand changes due to several different reasons. One reason is the continuing increase in traffic as economic growth and technology evolve, while the infrastructures remain relatively stagnant. Another reason is changes in demand pattern because of external forces such as unusual events and land use development policies. Therefore, an important issue for a transportation system is to have adequate capacity to accommodate changes in traffic demand. Feitelson and Salomon defined network flexibility as the ease with which a network can adjust to changing circumstances and demands, both in terms of infrastructures and operations (Feitelson & Salomon, 2000). It consists of node flexibility, link flexibility, and temporal flexibility. Node flexibility is defined as the ease with which network nodes can be located. Link flexibility depends on the ease and cost of locating an additional link between nodes, thus increasing network connectivity. Temporal flexibility refers to the ability to sequence infrastructure investments and the degree to which use of the infrastructure requires coordination among users. However, the approach is a qualitative assessment using a subjective rating scheme to measure flexibility. Values of flexibility might be varied depending on different perceptions.

While capacity reliability reflects the performance of the system when the supply or the capacity of system components is uncertain capacity flexibility of a transportation system should be considered to reflect the performance of the system under demand changes in terms of traffic volume and pattern due to the imposed external changes(Chen et al., 2002). Network flexibility addresses spatial organization in various infrastructure such as communications and transportation planning and engineering practices. Cho stated that transportation flexibility could be viewed as a multidimensional concept comprised of such parameters as performance, operating cost, and network design (Cho, 2002). Flexibility of a transportation system can be evaluated in typical performance parameters such as system capacity, origin–destination connectivity, and travel time. Morlok and Chang formalized the definition of capacity flexibility for a freight transportation system, which is the ability of a transport system to accommodate changes in traffic demand while maintaining a satisfactory level of performance (Morlok & Chang, 2004). Capacity flexibility can be quantified by estimating the maximum system capacity or the amount of traffic a system can handle. Two interpretations of flexibility are measured. The first is the range of changes in demand that the system can accommodate. In this case, the demand pattern is fixed. The second is the amount of traffic volume that can be accommodated when deviation of the base traffic pattern is permitted. Sun et al. further extended the work of Morlok and Chang (2004) by making three enhancements: treatment of uncertainty in future traffic pattern, incorporation of volume delay functions to account for congestion effect and level of service constraint to model service quality, and adoption of a stochastic traffic assignment procedure to enhance its routing options(Sun, Turnquist, & Nozick, 2006). These enhancements are considered useful for assessing a degradable transportation system with demand changes.

2.2.3 Vulnerability

The concept of vulnerability has been introduced in several fields including psychology, sociology, political science, economics, epidemiology, biology, environmental and geosciences, and engineering (McEntire, 2005). However, there is no generally accepted definition of the concept vulnerability even if we only consider technical, or engineering applications (Petreska et al., 2010). Einarsson and Rausand defined the concept of vulnerability of industrial systems in relation to risk

and system survivability (Einarsson & Rausand, 1998). They discussed premises, facilities, and production equipment, including human resources, human organization and all its software, hardware, and net-ware in industrial systems, that may weaken or limit system ability to endure threats and survive accidental events that originate both within and outside the system boundaries. The discussion is illustrated by referring to a number of previous industrial accidents. They compared the general scope of vulnerability analysis to traditional risk analysis approaches and point that a general procedure for vulnerability analysis in two steps, including building of scenarios and preparation of relevant worksheets, is described and discussed. Berdica defines vulnerability in the road transportation system as a susceptibility to incidents that can result in considerable reductions in road network serviceability (Berdica, 2002). In the field of information security, vulnerability is commonly thought of as a weakness in the security system that might be exploited to cause harm or loss. Morakis et al. (Morakis, Vidalis, & Blyth, 2003) define vulnerability as a measure of the exploitability of a weakness". In structural engineering, the term vulnerability is often used to capture the susceptibility of a component or a system to some external action. Thus, a structure is vulnerable if any small damage produces disproportionately large consequences(Agarwal, Blockley, & Woodman, 2003) . Finally, vulnerability is also a topic in mathematics. In the branch of discrete mathematics called graph theory, vulnerability implies a lack of resistance of the graph to the deletion of nodes and edges (Barefoot, Entringer, & Swart, 1987).

Satish V. Ukkusuri (Ukkusuri & Patil, 2009) assessed the importance of highway transportation networks using travel time as the performance measure to assess criticality. Localized level-of-service (LOS) measures such as the volume/capacity ratio (Bremmer, Cotton, Cotey, Prestrud, & Westby, 2004; Dheenadayalu, Wolshon, & Wilmot, 2004) are used to identify the critical highway segments. Ham and Lockwood identify critical assets in the Nation's highway transportation network (Ham, Lockwood, & PB, 2002). They define critical assets as: those major facilities the loss of which would significantly reduce interregional mobility over an extended period and thereby damage the national economy and defence mobility. They identify the critical assets based on several criteria: casualty risk, economic disruption, military support function, emergency relief function, national

recognition, and collateral damage exposure. The localized approach (volume/capacity ratio), however, may not enable traffic engineers and planners to identify the most critical highway segments or corridors in terms of maximizing system-wide, travel-time benefits associated with a highway improvement project. Bremmer et al. point out that traditional congestion measurements are based on volume and capacity information, but are often inadequate in many cases (Bremmer et al., 2004). In contrast, D.M. Scott et al. argue that the a system-wide approach should be focused on but not the existing localized based on volume/capacity ratio planning approach to identifying critical infrastructure and evaluating network performance(Scott, Novak, Aultman-Hall, & Guo, 2006). And they define a measure, the Network Robustness Index (NRI), to evaluate the critical importance of a given highway segment to the overall system as the change in travel-time cost associated with rerouting all traffic in the system should that segment become unusable. The user equilibrium assignment model is used to get travel time and the methodologies are applied in three hypothetical road networks.

$$NRI_a = c_a - c \tag{1}$$

Where NRI_a is the NRI value of link a, c_a is the travel time cost of removing link a, c is this travel time cost of the system-wide that incurred when all links are present in the network.

$$c_a = \sum_a t_a x_a \, \delta_a \tag{2}$$

Where, t_a is the travel time in link a, x_a is the traffic flow in link a, δ_a=0 when link a is removed, otherwise, equal 1.

$$c = \sum_a t_a x_a \tag{3}$$

Often the importance of transportation infrastructure is accentuated by special scenarios. A case in point is the importance of certain links and nodes in emergency evacuation scenarios. Murray Tuite studied the problem of identifying vulnerable transportation infrastructure under emergency

evacuation (Murray-Tuite & Mahmassani, 2003). The problem is represented as a game played between an evil entity and the traffic management agency (TMA). The evil entity seeks roads with higher disruption index and the TMA routes vehicles trying to avoid the vulnerable links. Unlike other transportation network evacuation models, her formulation also describes household decision making behaviour in an emergency evacuation. More recently, advanced modelling techniques based on stochastic programming and variational inequalities have been developed. For example, Liu and Fan develop a formulation of the network retrofit problem in stochastic programming framework (Fan, Liu, Lee, & Kiremidjian, 2009). The problem goes a step further than identifying critical infrastructure; they prioritize network retrofit strategies based on the importance of facilities and available budgets. Chen et al. developed a network-based accessibility measure using a combined travel demand model for assessing vulnerability of degradable transportation networks (Chen, Yang, Kongsomsaksakul, & Lee, 2007). They formulate the combined travel demand model as a variational inequality problem. Jones defined accessibility as a term related to the ease of reaching a destination concerning the opportunity provided by the transport system for people to join in a particular activity from a given location(Jones, 1981).

Individuals from specific locations in a region may participate in activities such as employment, education, shopping, trade and commerce that take place in other physical locations in and around the region and use a transport system to gain access to those locations (Taylor, d'Este, & Nicholson, 2004). Taylor and D'Este have defined vulnerability using this notion. 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 (Taylor & D'Este, 2007). 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. This definition can then be further refined by the selection of specific indices of accessibility. Morris, Dumble and Wigan think most of the confusion in accessibility measures stems from fundamental differences of opinion. There is a basic dilemma in choosing between "process"indicators (measures of the supply characteristics of the system and/or individuals) and "outcome" indicators (such as

actual use and levels of satisfaction). On the one hand accessibility may be interpreted as a property of individuals and space which is independent of actual trip making and which measures the potential or opportunity to travel to selected activities(Morris, Dumble, & Wigan, 1979). Alter natively, it may be held that "proof of access" lies in the use of services and participation in activities, not simply in the presence of opportunities. Consequently there is a tendency to want to measure accessibility in terms of actual behaviour. Koenig, Niemeier and Primerano provide discussions of alternative indices (Koenig, 1980; Niemeier, 1997; Primerano & TAYLOR, 2003). Taylor and D'Este (2004) proposed indices such as generalized travel cost and Hansen integral accessibility index to judge the vulnerability, or as comparison in the case of strategic level networks.

Jenelius et al. used the increase in generalized travel costs weighted by the satisfied or unsatisfied demand when network links are closed as a measure of vulnerability for a case study in Northern Sweden(Jenelius, Petersen, & Mattsson, 2006), using the terms "importance" and "exposure", similar to Nicholson and Du(Nicholson & Du, 1994). Di Mangi et al. obtained a link weakness index by looking at how important each link is for the overall set of origin/destination (o/d) pairs, by assessing how many o/d paths share the same link, based on probabilistic path choice models for calculating the paths(Di Gangi & Luongo, 2005). In comparison it can be said that Di Mangi's method is more concerned with connectivity and less with increase in travel cost, and hence, Jenelius' method is more applicable in calculating the socio-economic impact of road network vulnerabilities. Husdal suggests a weighted multi-criteria decision approach, where, link closures or degradations are assessed by various categories of effect and the severity of the impact, thus allowing for the assessment of individual effects or impacts(Husdal, 2005).

2.2.4 Originality of this study

Under the framework of vulnerability research about transportation network. This study attempts to find a methodology to properly address the character of logistics transportation network vulnerability. Total generalized cost is proposed to measure the performance of logistics transport networks considering both time value and transport cost. Multiple transport modes are considered in logistics transportation networks including highway, railway, and maritime. The vulnerability

assessment is measured by consequence of network degradation, which is quantified by total generalized cost of the network. Vulnerability assessment is conducted on both link and node levels. A computer program is made to apply vulnerability scanning into large scale complex transportation networks in reasonable time and computational efficiency. Additionally, seismic vulnerability index is also proposed to evaluate network vulnerability under seismic disasters. The seismic vulnerability index considers both the consequence of network degradation and also the probability of degradation caused by seismic disaster. The results will be helpful in making reinforcement policy for resisting seismic damage. The above methodologies are applied in study networks, consisting of Hokkaido logistics transportation networks. Finally, visual results of the study network are demonstrated using Geographic Information System (GIS) technology.

Different from the existing research about vulnerability assessment in passenger transport, this study focuses on logistics transportation networks, describing the vulnerability in multiple modes logistics transport systems. The concept of vulnerability analysis is related to evaluating the consequences of network degradation caused by incidents such as social or natural disasters. The seismic vulnerability index proposed in this study considers not only the consequences of network degradation but also the probability of degradation. This targeted analysis is helpful to realize concrete steps to mitigate the influence of specific disasters. This study is based on the background of increasing threats to transportation systems and increasing cost of transport network degradation. The results are practical and important for assisting policy makers to mitigate vulnerability of transportation systems.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Generalized cost in logistics transport network

Most transportation users tend to seek the shortest travel time route, however, travel time is not the only thing the users care about in logistics networks. They may shift from the shortest travel time route when other factors such as economic cost are considered. The optimal transport provides a link between products and customers with both minimum time and cost. However, in the real world these two are of a conflicting nature; air transport is faster but also more expensive than shipping. Hence, any model or procedure developed to evaluate the performance of the logistics transport network must seek a trade-off between these factors. This study proposes the generalized cost in the logistics transport network C_g as the index to find the optimal route between each logistics origin (supplier place) and destination (market place). From the logistics transport network user perspective, the generalized cost represents the trade-off between time consumption and travel cost because it includes both time value and cost. Broadly speaking, they are the real payment (money or other entities) and the bodiless cost such as time value cost of the specific route as shown in equation (4).

$$C_{g(i)} = C_{(i)} + T_{(i)} \times \alpha \tag{4}$$

Where,

$C_{g(i)}$: generalized cost of logistics transport in link i,

$C_{(i)}$: monetary cost of logistics transport in link i,

$T_{(i)}$: logistics travel time in link i,

α: time value multiplier.

In order to reflect the real logistics transport cost and at the same time simplify the calculation, only the costs that influence the user's route decision making are included in this analysis. The real

payments include fuel consumption, driver payment in a highway network, and container payment in both railway and shipping networks. These costs are denoted by $C_{(i)}$ meaning how much the user has to pay for using link i. Given that logistics is so sensitive to time, the time value is also included as one important part of logistics value, which is certainly another major factor of a logistics transport network user's route decision. Time values in a transport system mostly depend on the types of load it serves. For example, the more time sensitive and the more valuable the loads are, the higher the time values of their transport. Considering the character of logistics, time value cost is decided by travel time $T_{(i)}$ and time value multiplier α which depends on load type. Generalized logistics transport cost in the specific facility i can be evaluated by $C_{g(i)}$, however, it needs to be further noted that $C_{g(i)}$ here is transport cost per unit logistics which is convenient to quantify the logistics transport cost in multi-mode networks.

The transport cost of unit logistics is not enough to evaluate the whole logistics transport network, so logistics demands are considered to include all network users' benefits. The least generalized cost path between origin (o) to destination (d) is denoted as $C_{g(od)}$, is the shortest path between od pair as shown in equation (5). In the following case study section, the shortest paths between od pairs are searched by the Dijsktra algorithm, which greatly improve the efficiency of computer programming. Then the total generalized cost of all od pairs are calculated based on $C_{g(od)}$ and the logistics travel demands of each od pair as shown in equation (6).

$$C_{g(od)} = \sum_{S} C_{g(i)} \tag{5}$$

Where,

$C_{g(od)}$: generalized cost of unit logistics transported between od pair,

$C_{g(i)}$: generalized cost in link i,

S: set of links in the shortest path between od pair.

$$C_t = \sum_{od}^{OD} C_{g(od)} \times d_{od} \tag{6}$$

Where,

C_t: total logistics transport cost,

od: od pair,

OD: set of all od pairs,

$C_{g(od)}$: generalized cost of unit logistics transported between od pair,

d_{od}: logistics travel demands between od pair.

In the following case study section, the total generalized cost is not only used to evaluate current logistics network but also predict the performance of planning network.

3.2 The shortest path problem

Shortest path problems are among the most studied network flow optimization problems. Since the end of 1950's, more than thousand scientific works have been published in the literature, most of them in journals and conference proceedings concerning general combinatorial optimization on graphs, but also in numerous specialized journals. One of the most interesting application fields is transportation. In many transportation problems, shortest path problems of different kinds need to be solved. These include both classical problems, for example to determine shortest path (under various measure, such as length, cost and so on) between some given origins/destinations pairs in a certain area, and also nonstandard versions, for example to compute shortest paths either under additional constraints or on particular structures graphs. Due to the nature of applications, transportation scientists need very flexible and efficient shortest path procedures, both from the running time point of view and in terms of memory requirements. Shortest path routines are never absent from any computer code used in transportation analysis and planning. This explains why, together with the

increasing role of large scale mathematical models, interest in efficient shortest path algorithms has been growing, and an enormous number of algorithms have been proposed.

There are popular classification about the shortest problems. It is divided into weighted shortest path problem and unweighted shortest path problem. Simple Breadth-first-search is one of the solutions for shortest searching in unweighted network simple Breadth-first-search. The shortest path problem in weighted network includes several variations: the single-pair shortest path problem, the single-source shortest path problem, the single-destination shortest path problem, and the all-pairs shortest path problem. The single-pair shortest path problem is about searching shortest path between one single pairs in directed or undirected graph. The single-source shortest path problem, in which the shortest paths are searched from a source vertex to all other vertices in the graph. The single-destination shortest path problem, in which the shortest path form all vertices in the directed graph to a single destination vertex. This can be reduced to the single-source shortest path problem by reversing the arcs in the directed graph. The all-pairs shortest path problem, in which the shortest paths between every pair of vertices in the graph are searched. There are also some popular solutions for these problems. Dijkstra's algorithm and Bellman–Ford algorithm solve the single-source shortest path problem and Bellman–Ford algorithm is applicable if edge weights may be negative. A* search algorithm solves for single pair shortest path using heuristics to try to speed up the search. Floyd–Warshall algorithm and Johnson's algorithm solve all pairs shortest paths and the latter one may be faster than Floyd–Warshall on sparse graphs. Viterbi algorithm solves the shortest stochastic path problem with an additional probabilistic weight on each node(Cherkassky, Goldberg, & Radzik, 1996).

In this study, the logistics transportation networks are simplified to weighted and undirected graphs. The shortest path in this kind of graph is described as follows.

Let $G = (V, E)$ be a weighted graph, with weight function $w: E$ mapping edges to real-valued weights. If $e = (u, v)$, $w(u, v)$ will be written as $w(e)$. The length of a path$p = (v_0, v_1, v_2, v_k)$ is the sum of the weights of its constituent edges:

$$\text{Length}(p) = \sum_{i=1}^{k} w(\, v_{i-1}, v_i) \tag{7}$$

The shortest path p_s is minimized $\text{Length}(p)$ of all possible routes between u and v. When each edge in the graph has unit weight or, this is equivalent to finding the path with fewest edges.

The shortest route from origin to destination in logistics transportation networks is simplified into the single source shortest path problem in a weighted and undirected graph. Dijsktra algorithm is applied to solve this problem. The shortest problem in logistics transportation networks is measured by generalized cost.

Dijkstra's algorithm, conceived by computer scientist Edsger Dijkstra in 1956 and published in 1959 (Dijkstra, 1959), is a graph search algorithm that solves the single source shortest path problem for a graph with non-negative edge path costs, producing a shortest path tree. This algorithm is often used in routing and as a subroutine in other graph algorithms. For a given source vertex (node) in the graph, the algorithm finds the path with lowest cost (i.e. the shortest path) between that vertex and every other vertex(Mehlhorn & Sanders, 2008) (although Dijkstra originally only considered the shortest path between a given pair of nodes (Dijkstra, 1959)). It can also be used for finding costs of shortest paths from a single vertex to a single destination vertex by stopping the algorithm once the shortest path to the destination vertex has been determined. For example, if the vertices of the graph represent cities and edge path costs represent driving distances between pairs of cities connected by a direct road, Dijkstra's algorithm can be used to find the shortest route between one city and all other cities.

The Dijkstra's algorithm is described as following (Dijkstra, 1959):

The branches are subdivided into three sets:

1. the branches definitely assigned to the tree under construction (they will form a subtree) ;

2. the branches from which the next branch to be added to set 1, will be selected;

3. the remaining branches (rejected or not yet considered)'

The nodes are divided into two sets:

A. the nodes connected by the branches of set 1,

B. the remaining nodes (one and only one branch of set 2 will lead to each of these nodes).

Starting from the initial node as the only member of set A, and by placing all branches that end in this node in set 2. To start with, set 1 is empty. From then onwards, the following two steps are repeated.

Step 1. The shortest branch of set 2 is removed from this set and added to set 1. As a result one node is transferred from set B to set A.

Slep 2. Consider the branches leading from the node that has just been transferred to set A, to the nodes that are still in set B. If the branch under consideration is longer than the corresponding branch in set 2, it is rejected; if it is shorter, it replaces the corresponding branch in set 2, and the latter is rejected.

We then return to step 1 and repeat the process until sets 2 and B are empty.

The branches in set 1 form the shortest path tree.

To find the shortest path between two intersections on a transportation network, a starting point and a destination, the order is conceptually simple: to start, mark the distance to every intersection on the map with infinity. This is done not to imply there is an infinite distance, but to note that intersection has not yet been visited; some variants of this method simply leave the intersection unlabelled. Now, at each iteration, select a current intersection. For the first iteration, the current intersection will be the starting point and the distance to it will be zero. For subsequent iterations, the current intersection will be the closest unvisited intersection to the starting point.

From the current intersection, update the distance to every unvisited intersection that is directly connected to it. This is done by determining the sum of the distance between an unvisited intersection and the value of the current intersection, and relabeling the unvisited intersection with this value if it is less than its current value. In effect, the intersection is relabelled if the path to it through

the current intersection is shorter than the previously known paths. To facilitate shortest path identification, in pencil, mark the road with an arrow pointing to the relabelled intersection if it is labelled or relabelled , and erase all others pointing to it. After the distances to each neighbouring intersection are updated, mark the current intersection as visited and select the unvisited intersection with lowest distance from the starting point, or the lowest label, as the current intersection. Nodes marked as visited are labelled with the shortest path from the starting point to it and will not be revisited or returned to.

Continue this process of updating the neighbouring intersections with the shortest distances, then marking the current intersection as visited and moving onto the closest unvisited intersection until the destination have been marked as visited. Once the destination is marked as visited as is the case with any visited intersection, the shortest path to it is determined.

3.3 Vulnerability scanning of logistics transport network

The generalized cost is proposed to assess the performance of logistics transport networks, however vulnerability evaluation is prediction involving comparison with a reference status. Different vulnerability indices have been developed, as shown in the literature review. Most of them stated the network's normal performances as the reference status and evaluated the vulnerability of facilities in network when they degrade. This study uses the ratio of these two states as the vulnerability index of facilities in the multi-mode logistics transport networks as shown in equation (8).

$$V_{(k)} = \frac{\Delta C_{t(k)}}{C_t} = \frac{{C_{t_{(k)}}}' - C_t}{C_t} \tag{8}$$

Where,

$V_{(k)}$: vulnerability index of component k,

$\Delta C_{t(k)}$: total logistics transport cost difference when component k degrades ,

C_t: total logistics transport cost in the normal status,

$C_{t_{(k)}}{}'$: total logistics transport cost after component k degrades.

Links and nodes are usually abstracted to basic components of the transportation network representing road section and intersection joining several sections. Links seem to be the most significant component when network vulnerability is evaluated; nevertheless, degradations don't always isolate an unlucky link but involve more conjoint links when disasters such as snowstorms and floods occur. In this study both link and mode vulnerability measurements are developed. Each link of transportation network is supposed to be disrupted when its vulnerability is evaluated. Shown as Figure 2, when a link is disrupted, its capacity will decrease to 0 meaning its function 100% failure.

Figure 2 Link disruption

Link failure represents the scenario that threats happen to individual link of the network. However, threats also can be area covering that will disrupt several neighbouring links. So node vulnerability is propose here to represent area vulnerability in addition to link vulnerability. When a link is disrupted, all links connected to it will be disrupted too. Node disruption means that the node and the area around it fail in the network operation shown as Figure 3.

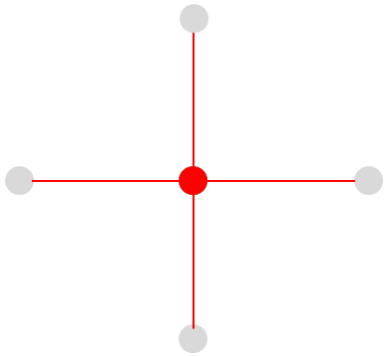

Figure 3 Node disruption

Vulnerability index is a measurement of degradation of network performance when some components are disrupted. However, the concept of network vulnerability involves comparisons of components importance to the whole network function. Vulnerability scanning is developed to evaluation vulnerability index of each component. When component k's vulnerability index is calculated, it is supposed to fail, and it is supposed to recover after its vulnerability index calculation is finished. This procedure is repeated until all vulnerability index calculation of components have been done. This algorithm is shown as Figure 4.

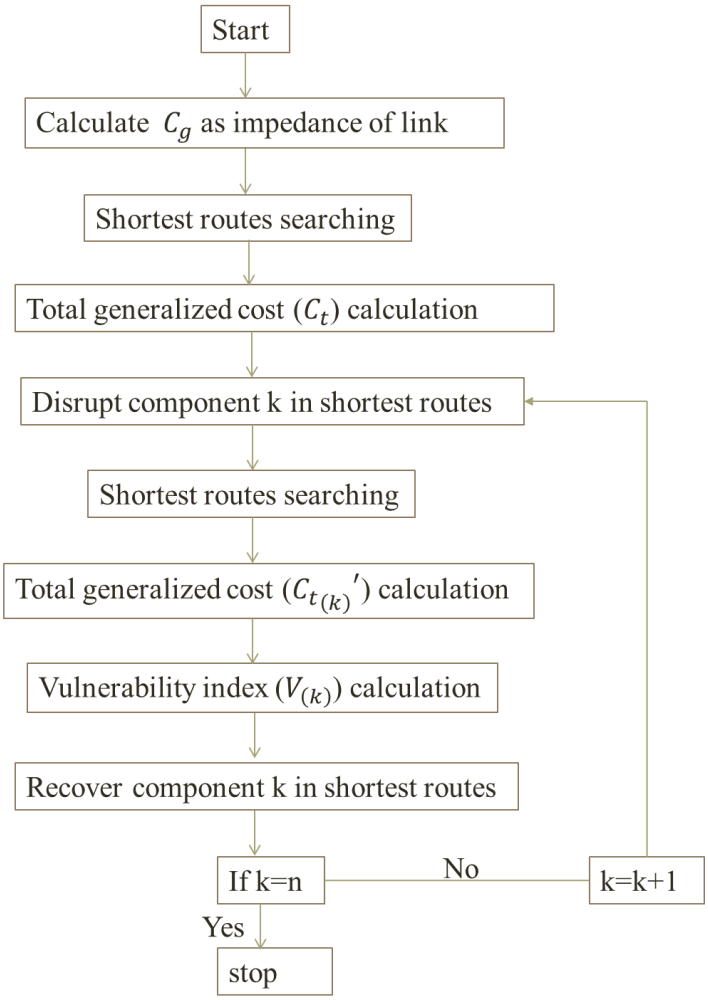

Figure 4 vulnerability scanning algorithm

In addition, researchers have pointed out that a vulnerability of transportation network shows different results as the traffic demands increase (Ukkusuri & Patil, 2009). The vulnerability scanning in this study is also conducted under different logistics traffic demands volume, and these demands change not only on volume but also distribution.

CHAPTER 4 VULNERABILITY SCANNING IN MULTIPLE LOGISTICS TRANSPORT NETWORKS

4.1 Study network

Japan, a country of islands, extends along the eastern or Pacific coast of Asia. The main islands (sometimes referred to as the Home Islands), running from north to south, are Hokkaido, Honshu (or the mainland), Shikoku, and Kyushu. Naha on Okinawa in the Ryukyu archipelago is over 600 km to the southwest of Kyushu shown as Figure 5. Naha on Okinawa in the Ryukyu archipelago is over 600 km to the southwest of Kyushu. In addition, about 3,000 smaller islands may be counted in the full extent of the archipelago that comprises greater Japan. Honshu is the largest and most populous region and referred to as the Japanese mainland. It has 60% of the total area of Japan and 80% of the total population. Hokkaido, the northernmost of Japan's four main islands, is the country's second largest island. Hokkaido is the largest prefecture among the 47 of Japan and is famous for many great national parks and agricultural areas. Compared with highly populated Honshu, Hokkaido has a lower population density, as shown in Figure 6. The population density of Hokkaido is around 66 persons/km^2, which is the lowest of the 47 prefectures and much lower than the national average of 336 persons/km^2. In addition to low population density, Hokkaido contains good cultivated land that makes it a strategically important agricultural region in Japan.

Figure 5 Main islands of Japan (source: http://www.gojapango.com/travel/images/japan_map_islands.gif)

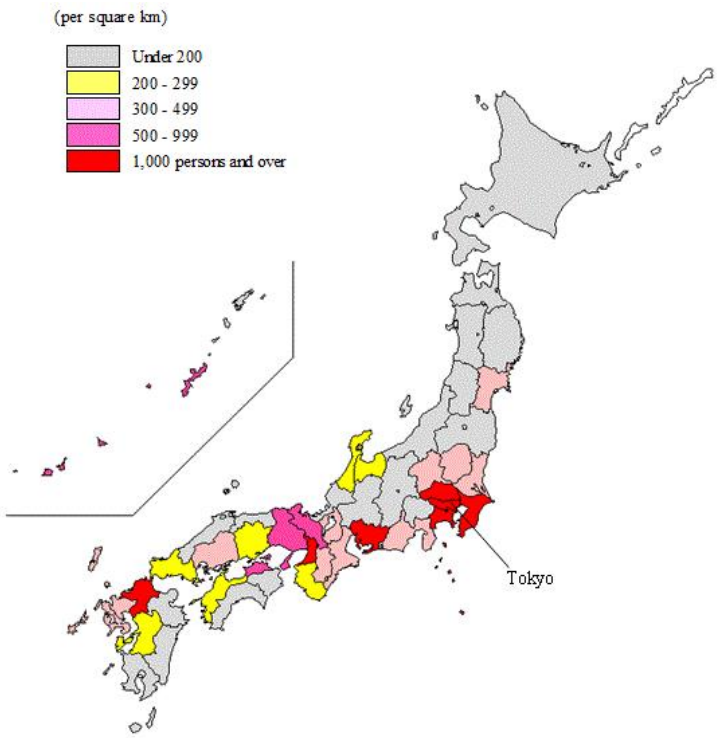

Figure 6 Population density by prefecture in Japan 2010 (source: Statistics Bureau of Japan)

According to the report of the Department of Agriculture Hokkaido Government Hokkaido (2011), Hokkaido has some 25% of the cultivated land of Japan, which supplies about 20% of the domestic calorie contribution and 12% of the total agriculture product exports of Japan. However its inhabitants make up only 4.3% of the Japanese population, so most local agriculture products have to be transported out of Hokkaido to Honshu. On the other hand, most industrial product like commodities needs to be transported from Honshu to Hokkaido. These consist of main volume of logistics goods between Hokkaido and Honshu. Large agriculture output and small population consumption results in different volume between the goods transported out of and the goods transported into Hokkaido. The logistics traffic volume is divided into two directions. One direction is mainly agricultural outputs including fresh vegetables, milk and milk products that need to be transported out of Hokkaido to Honshu, simply named by "export" in the following. The other direction is the industrial products like commodities that need to be transported into Hokkaido from Honshu simply named by "import" in the following. Freight transportation modes between Hokkaido and Honshu include one rail tunnel, several shipping routes and several airlines. Figure 7 and Figure 8 show the transport modes share in logistics transport between Hokkaido and Honshu.

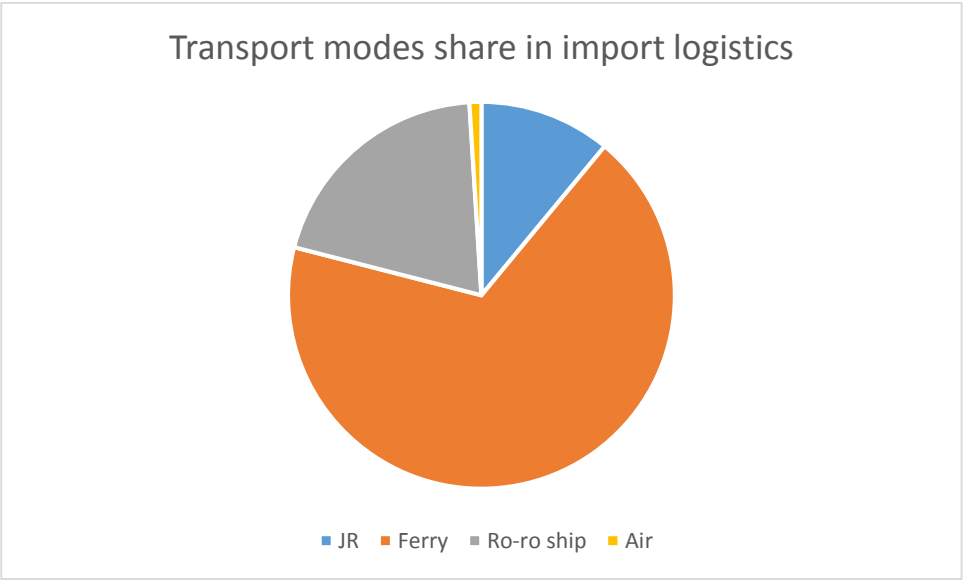

Figure 7 Transport mode share in import logistics

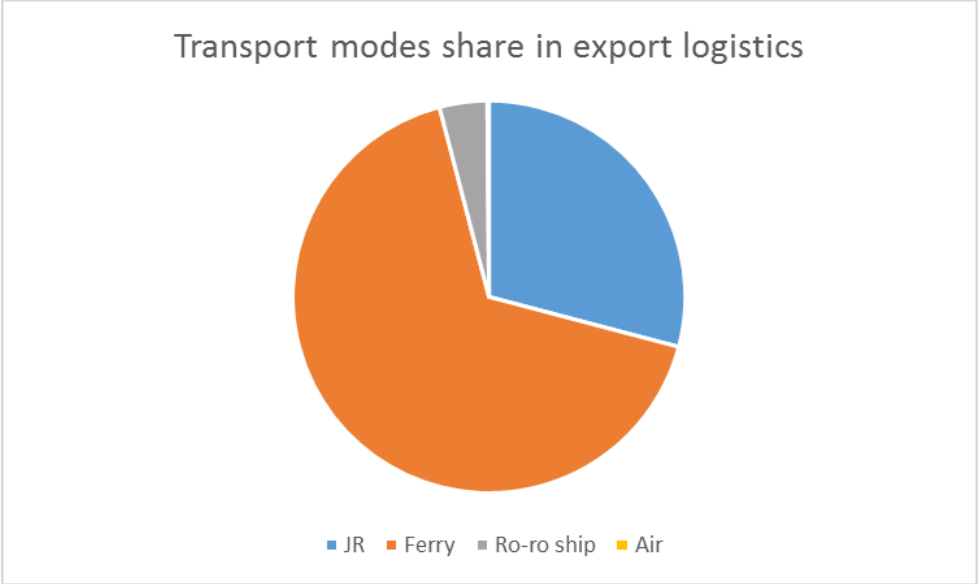

Figure 8 Transport mode share in export logistics

As Figure 7 and Figure 8 show, freight airlines' shares are quite small in both export and import logistics volumes. This study focuses on railway and shipping transport modes connecting Hokkaido and Honshu to simplify the analysis. There is one railway tunnel and 5 shipping routes connecting Hokkaido and Honshu. These 5 shipping routes connect to 3 ports inside Hokkaido, which are Tomakomai, Hakodate, and Otaru, as shown in Figure 9, and the ports in Honshu are simplified to one location, which is Oarai. These 3 ports are also connections between the highway network and maritime routes. The railway tunnel connecting Hokkaido and Honshu is the Seikan Tunnel, which is a 53.85 km railway tunnel with a 23.3 km long portion under the seabed. The Seikan Tunnel is both the longest and the deepest operational main-line rail tunnel in the world. The location of the Seikan Tunnel is shown in Figure 10.

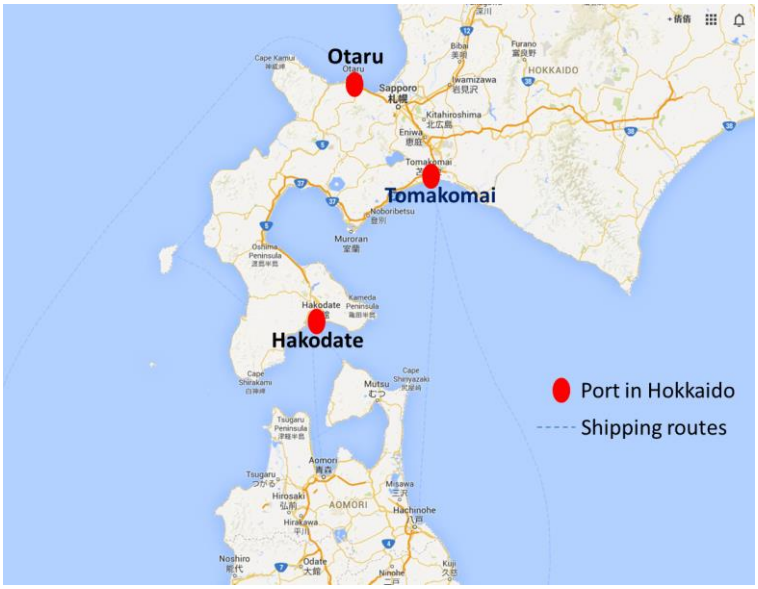

Figure 9 Ports in Hokkaido and shipping routes between Hokkaido and Honshu (source: Google Maps)

Figure 10 Railway connection between Hokkaido and Honshu (source: Google Maps)

This study network consists of 900 km of express highway, 6361 km of national highway, 4533 km of prefecture arterial highway, and 3176 km of railway, representing the current situation of the Hokkaido highway and railway logistics transport network, as shown in Figure 11. In addition to this map, there are also 5 shipping routes connecting Hokkaido and Honshu by ships.

There are 10 freight stations connecting the highway network and the railway network, which are shown as purple circles in Figure 11. Hokkaido is divided into 14 areas according to the local administrative divisions. These 14 areas are assigned to be both agriculture product origins and industrial product and materials destinations. These 14 origins/destinations are shown as red circles in Figure 11.The industrial product origin/agriculture product destination in Honshu is Aomori freight terminal by railway and Oarai port near Tokyo by maritime routes.

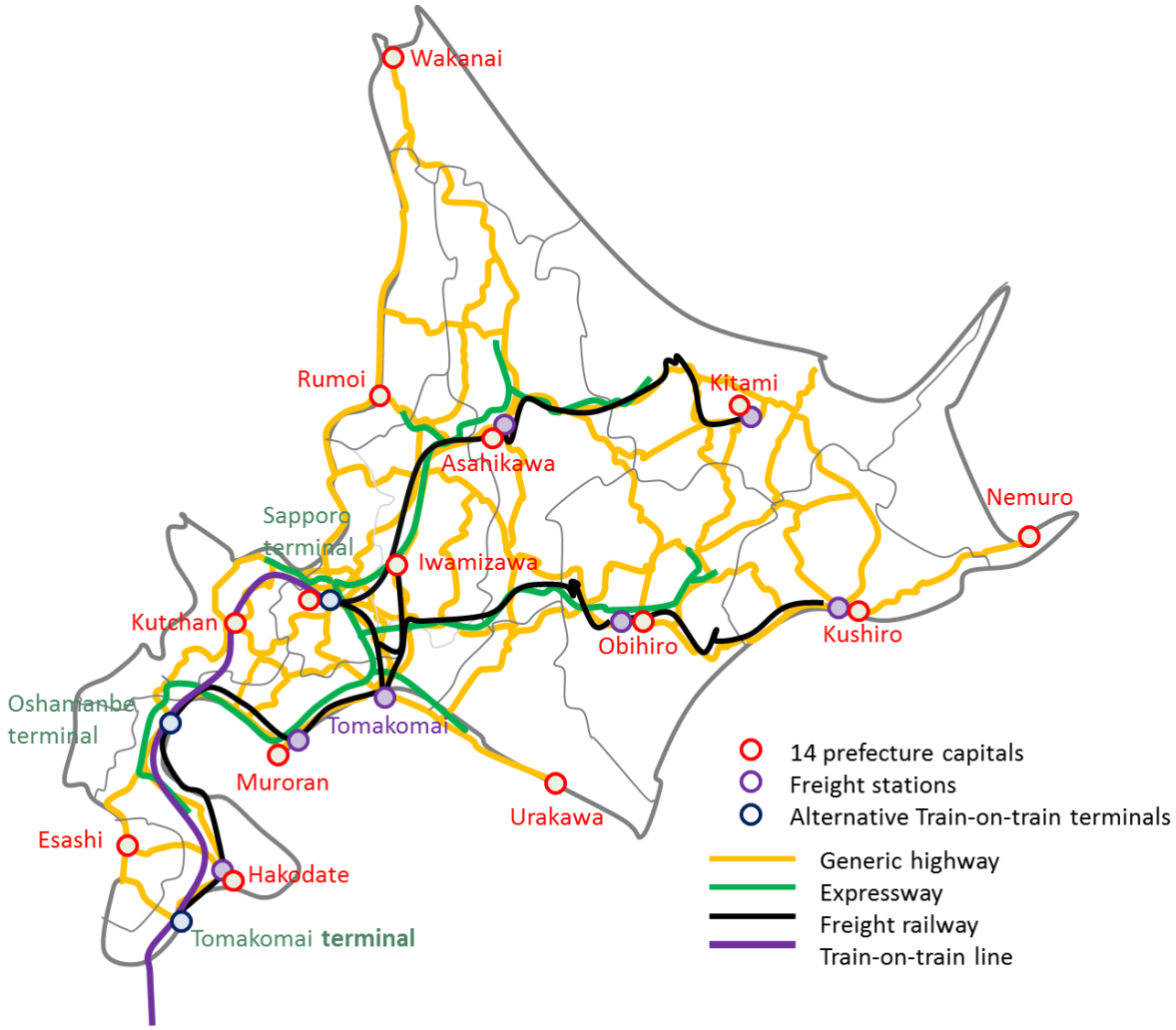

Figure 11 Planning Logistics Transport Network of Hokkaido.

As mentioned above, the logistics transport volumes between Hokkaido and Honshu are divided into export and import. The import logistics volume is quite stable in time, however the export logistics volume has typical seasonal character caused by agriculture products shown by the historical data in Figure 12; export logistics volume in September is more than 4 times of May. To determine logistics transport vulnerability to this fluctuation, export logistics volumes in two peak months (May and September) are chosen to represent the fluctuation of export demands in vulnerability scanning. The categories of logistics traffic demands include "Export in average", "Import in average", "Export in September" and "Export in May" scenarios. The logistics traffic demands data used in this study is from Hokkaido logistics statistics and logistics volumes are averaged to per day from the yearly amount. The export and import volume between14 administrative divisions of Hokkaido and Honshu are shown as Figure 13.

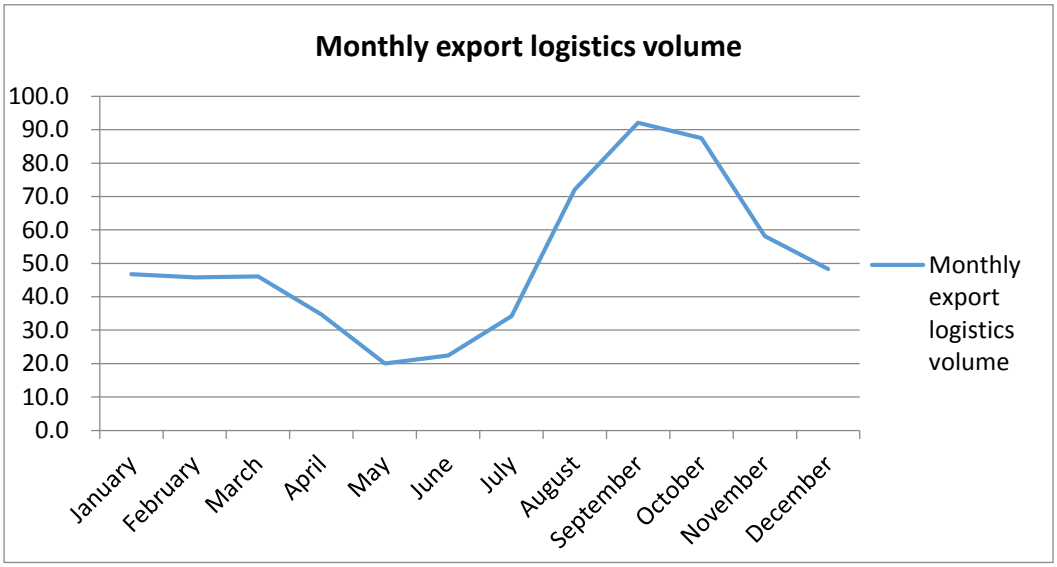

Figure 12 Averaged Monthly Export Logistics Demands (1000 Tons)

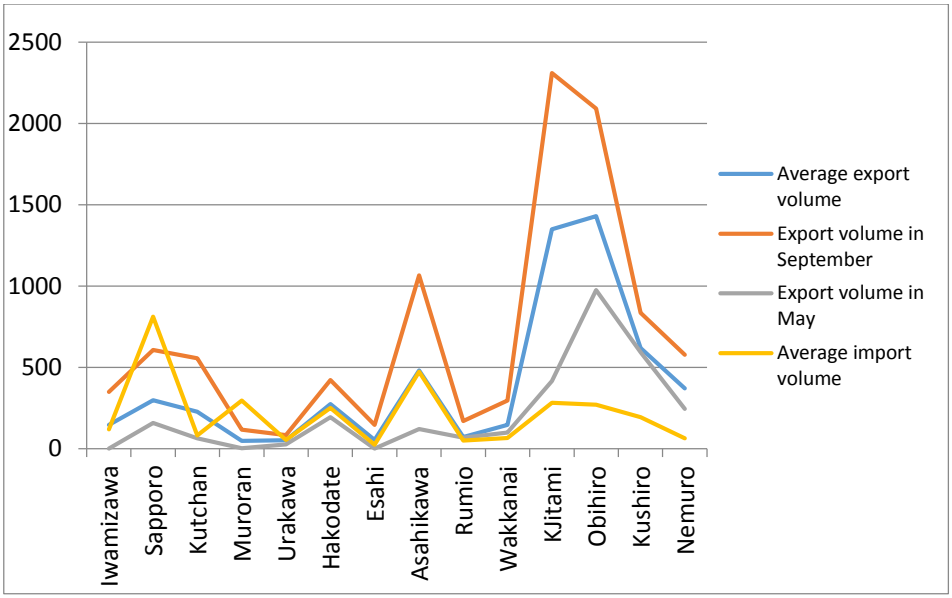

Figure 13 Diversified Logistics Demands (Tons/Day)

As mentioned in the methodology section, some parameters need to be determined before the methodology is used in a specific network. One of them is time value multiplier α, which depends on the type of logistics load. According to related research of the time value in the logistics industry in Japan, the time value multiplier α of agricultural products and other food is 240 JPY/hour, and products and materials of industry and commodity is 3240 JPY/hour (Murata, 2006). As for the standard vehicle capacity in the highway network, 10 ton is assumed because it is the average capacity of medium duty trucks which are popularly used in the Hokkaido logistics transport network.

4.2 High-speed railway planning of Hokkaido

High-speed rail is a type of rail transport that operates significantly faster than traditional rail traffic, using an integrated system of specialized rolling stock and dedicated tracks. Japan was the first country to build dedicated railway lines for high-speed travel. Known as the “bullet train” or Shinkansen, it began operations in 1964. High-speed trains normally operate on standard gauge tracks of continuously welded rail on grade-separated right-of-way that incorporates a large turning radius in its design. High-speed railways are currently regarded as one of the most significant technological breakthroughs in passenger transportation developed in the second half of the 20th century. At the

beginning of 2008, there were about 10,000 km of new high-speed lines in operation around the world. In total (including upgraded conventional tracks), more than 20,000 km of the world wide rail network was devoted to providing high-speed services to passengers willing to pay for shorter travel time and a quality improvement in rail transport (Campos & de Rus, 2009). Many countries have developed high-speed rail to connect major cities. While high-speed rail is usually designed for passenger travel, some high-speed systems also offer freight service. For instance, the French mail service La Poste owns a few special TGV trains for carrying postal freight.

The Shinkansen has made a tremendous contribution to the development of Japan by connecting people, products, work and life. Because of the mountainous terrain, the existing network consisted of narrow gauge (1.067m) lines, which generally took indirect routes and could not be adapted to higher speeds. Consequently, Japan had a greater need for new high-speed lines than countries where the existing standard gauge (1.435m) or broad gauge rail system had more upgrade potential. The Shinkansen uses standard gauge in contrast to the narrow gauge of older lines.

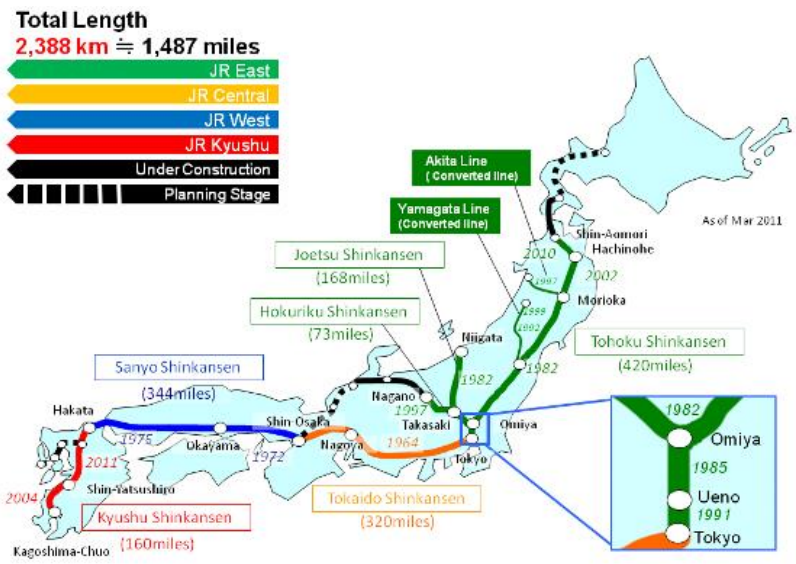

Figure 14 Shinkansen planning in Japan (source: Ministry of Land, Infrastructure, Transport and Tourism of Japan)

As the passenger demands greatly increase with economic development, the high-speed railway network will extend from Honshu (the main island of Japan) to Hokkaido, as shown in

Figure 14. Figure 15 shows that the high-speed railway is expected to pass through the strait (Tsugaru Strait) between Hokkaido and Honshu and go to Kikonai, Oshamanbe and finally arrive at Sapporo. There is only one railway tunnel crossing over the Tsugaru Strait. The high-speed trains will have to go through the Seikan Tunnel, and the old freight trains between Hokkaido and Honshu also need to be kept for logistics transport. There will be old freight trains on narrow gauge and high-speed trains on standard gauge operated simultaneously in the Seikan Tunnel, as shown in Figure 16. However, this coexisting system will probably cause safety issues. The traditional freight trains running on the narrow gauge have a high risk of being dislodged by the strong airflow when the high-speed passenger train, whose gauge is 1.435 m, passes by (Kitagawa, 2005). Operating them alternatively will be one option to solve this safety problem, but it will reduce the frequency of both high-speed passenger trains and old freight train that will not satisfy the increasing traffic demands.

The “Train-on-Train” concept was proposed by Hokkaido Railway Company in 2006 as one solution for the problems illustrated above. This concept involves loading traditional narrow gauge container wagons onto specially built standard gauge wagons of high-speed trains, which can be visually explained by “Train-on-Train”. These rail freight wagons will be operated at around 200 km/h, which will greatly improve the efficiency of the freight rail system. A sketch of the “Train-on-Train” concept is shown in Figure 17 and the operation is shown in Figure 18. On the hypotheses of “Train-on-Train” system, the high-speed freight railway will go along the planned high-speed railway from Aomori station to Sapporo station as Figure 15 shown. Along this planned railway line, there are several freight terminals which are possible “Train-on-Train” terminals in the high-speed freight railway planning. This study attempts to evaluate these schemes and find the one that optimally benefits the generalized cost of logistics transport.

Figure 15 The high-speed railway extension to Hokkaido (source: Japan Railway Construction Public Corporation)

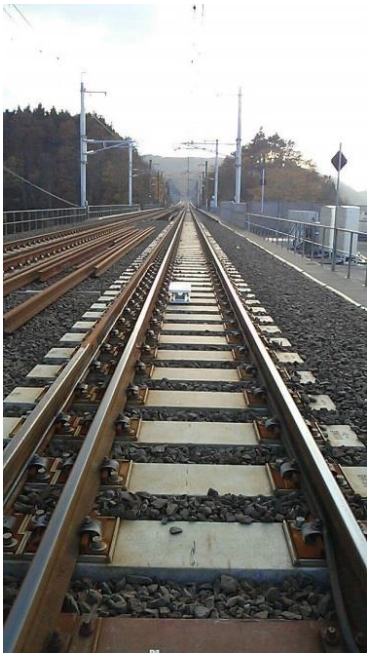

Figure 16 Narrow gauge and standard gauge tracks

Figure 17 Sketch of "Train-on-Train"

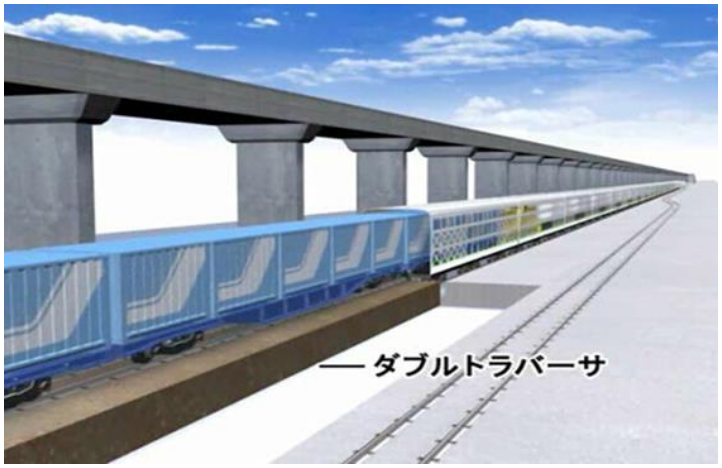

Figure 18 Operation of "Train-on-Train"

4.3 Generalized cost in multiple logistics transportation network

In this study, the travel cost and time in different transportation modes are calculated respectively. In highway logistics transport networks, trucks are assumed to be the only available vehicle, and one standard vehicle capacity is assumed for convenience in simulation. For one standard vehicle's single trip, the logistics transport cost and time is mostly related to transport distance. Travel time in link i is calculated with the link length l_i and average speed in this link v_i as shown in equation (9). The logistics transport cost in link i considers fuel consumption, toll and driver's

payment which can be regarded as labour cost increasing with working time as shown in equation (10).

$$T_{h(i)} = \frac{l_i}{v_i} \tag{9}$$

Where,

$T_{h(i)}$: travel time in link i in highway network,

l_i: length of link i,

v_i: average speed in link i.

$$C_{h(i)} = l_i \times f + To_i + T_{h(i)} \times p \tag{10}$$

Where,

$C_{h(i)}$: cost of logistics transport in link i in highway network,

l_i: length of link i,

f: fuel consumption per kilometre ,

To_i: toll of link i (in case that i is tolled facility),

$T_{h(i)}$: travel time in link i in highway network,

p: driver's payment per hour.

In the railway network, logistics travel time and transport costs are calculated in a different way. Travel time in a railway is decided by train schedules of departure and arrival. According to a freight railway company's management practices, even the loading and unloading have specific schedules arranged by railway companies in order to efficiently dispatch freight distribution. So the logistics travel time in railway networks is not only decided by distance. It should start from loading in the original freight rail station and end with unloading in the destination freight rail station.

However, there is usually more than one train with different speeds operating in the same interval and they may not have the same travel time. In this study, all the trains are assumed to run strictly according to the schedule, and average running time of all the trains passing through the same interval is simplified in the simulation as shown in equation (11). The logistics travel cost is related to transported load weight and distance in the railway network. For unit weight logistics, the travel cost is decided by distance. Similar to average travel time, the logistics travel cost is proposed as an average form as shown in equation (12).

$$T_{r(i)} = \frac{\sum_{j=1}^{n} T_{r(ij)}}{n} \tag{11}$$

Where,

$T_{r(i)}$: travel time in link i in the railway network,

$T_{r(ij)}$: travel time of train j in link i,

n: numbers of trains running in link i in a scheduling cycle (24 hours).

$$C_{r(i)} = \frac{\sum_{j=1}^{n} l_i \times b_{ij}}{n} \tag{12}$$

Where,

$C_{r(i)}$: travel cost in link i in railway network,

l_i: length of link i,

b_{ij}: transport fare of train j per kilometre in link i.

n: numbers of trains running in link i in a scheduling cycle (24 hours).

The shipping transport mode has similar features with the railway network. Logistics travel time is calculated based on the schedule of ships running in a scheduling cycle (24 hours). The averaged travel time is shown as equation (13). Logistics transport cost is charged by weight in

shipping routes. For the unit logistics weight, the cost is expressed by the average of all the ships running in the same route in a scheduling period shown as equation (14).

$$T_{s(i)} = \frac{\sum_{j=1}^{n} T_{s(ij)}}{n} \tag{13}$$

Where,

$T_{s(i)}$: travel time in link i in shipping route,

$T_{s(ij)}$: travel time of ship j in link i,

n: numbers of ships running in link i in a scheduling cycle (24 hours).

$$C_{s(i)} = \frac{\sum_{j=1}^{n} d_{ij}}{n} \tag{14}$$

Where,

$C_{s(i)}$: travel cost in link i in shipping routes,

d_{ij}: transport fare of ship j in link i,

n: number of ships running in link i in a scheduling cycle (24 hours).

Generalized cost in a multi-mode transport network is described above, and it will be an effective index to evaluate the performance of logistics transport networks. Supposing the logistics transport network users can perfectly control the interface between different transport modes, and there is no waiting time when the logistics switch between two different transport modes, the intermodal generalized cost is a sum of the different transport modes.

4.4 Simulation tools

C++ is a general purpose programming language. It has imperative, object-oriented and generic programming features, while also providing the facilities for low level memory manipulation. It is designed with a bias for systems programming with performance, efficiency and flexibility of use

as its design requirements. It has also been found useful in many other contexts, including desktop applications, servers and performance critical applications. It is a compiled language, with implementations of it available on many platforms.

C++ is used in this study to calculate link generalized cost, search shortest routes between od pairs, calculate the vulnerability index and do vulnerability scanning. Efficient programming will make vulnerability scanning applicable in complex transportation networks within reasonable time and computation consumption.

MapInfo Professional is a desktop geographic information system (GIS) software product produced by Pitney Bowes Software (formerly MapInfo Corporation) and used for mapping and location analytics. It provides tools to visualize, analyse, edit, interpret, understand and output data to reveal relationships, patterns, and trends. MapInfo also allows users to explore spatial data within a dataset, symbolize features, and create maps. It is used for a wide range of business applications in many industries. This professional software is used in this study to visualize the link vulnerability scanning results.

4.5 Data resources

Logistics traffic demands are divided into two directions in this study. One is logistics volumes transported out of Hokkaido into Honshu, which are mostly agriculture products named simply “export” in the following, and the other direction is logistics volume transported into Hokkaido from Honshu which is simply named “import” in the following. The export logistics volume is based on a survey report about agriculture and livestock products exported from Hokkaido that was conducted by Hokkaido regional development bureau in 2012. This report aimed to find out the volume of agriculture and livestock products exported from Hokkaido and the survey was distributed to 144 related enterprises and organizations and got 135 responses. The survey is about 31 kinds of fresh agriculture and livestock products including rice, wheat, soybean, fresh vegetable, and so on. It also includes 11 kinds of processed products including cheese, sugar, milk powder, and so on. The import logistics volume is based on a survey about logistics volume movement inter-region in

Japan. This survey was conducted by the Ministry of Land, Infrastructure, Transport and Tourism of Japan in 2011 and includes railway, truck and shipping transport modes covering all prefectures and subprefectures in Japan. The logistics volume includes 32 detailed classification of goods and is put into 9 general categories. The logistics volume transported into Hokkaido used in the following study case is based on this survey.

The links data in highway networks is based on numerical data of road networks of Hokkaido, which is digitized geographic information on topography of roads. The link information includes link name, link category, average speed, nodes of the link, and length of the link. Link name is the name of the road, and link category is divided in to 5 according its function (expressway, national highway, prefecture arterial road, and prefecture subsidiary road). Average speed is average travel speed on this link which varies with link type. Length of link is the travel distance on the link which is measured by kilometre. Nodes of a link are identification number of nodes connected with the link which will be used in programing for network analysis.

The railway and maritime networks data including travel time, travel cost, and train schedules are based on the documents released from Hokkaido freight railway companies and maritime companies which charge all rail and maritime freight transportation in Hokkaido. The travel time is based on train and shipping schedules, and travel cost is based on goods transport fare by railway and shipping. There are 10 main freight rail stations and 3 maritime ports connecting highway networks, railway networks, and shipping networks together.

4.6 Hokkaido high-speed freight railway network planning based on generalised cost

Under the high-speed railway planning frame, firstly high-speed railway planning is performed by evaluating generalized cost, and then network vulnerability is scanned on a planned transport network. When high-speed railway planning schemes are evaluated, averaged export and import logistics traffic demands are used. These are three alternative “Train-on-Train” terminals considered in this study. These terminals are on the same planning line and the number of terminals is the basis of this planning, so all the scenarios are divided into 3 categories by “Train-on-Train”

terminal numbers. Firstly, single “Train-on-Train” terminal scenario, with location taken to be one of those three candidate locations: “Sapporo”, “Kikonai”, and “Oshamanbe” represented by “s”, “k” and “o”, respectively. Secondly, two “Train-on-Train” terminals are taken to be constructed in two of the three candidate locations. These scenarios are notated as “s, k”, “s, o”, and “k, o”. Thirdly, three terminal scenarios are taken to be constructed in all three candidate locations notated by “s, k, o”.

Travel time in high-speed railway network is based on the distance and expected speed, while also considering reasonable transfer time. Travel cost refers to current freight trains running in the same line. Travel time in high-speed railway network is based on the distance and expected speed also considering reasonable transfer time and travel cost refers to current freight trains running in the same line. The total generalized logistics transport cost in different high-speed railway planning schemes are calculated. They are compared to the current situation, and from the results, the logistics transport cost is significantly reduced after high-speed trains are applied. Figure 19 shows the saved total generalized logistics transport cost by high-speed railways. “s, k, o” scheme reduces most sum cost (23 million JPY/day) in both export (6.5 million JPY/day) case and import (16.5 million JPY/day). But if construction and maintenance costs of terminals are considered, other options may keep better balance between cost and benefit, such as “s, k” has approaching cost saved (6.5 million JPY/day in export, 16.1 million JPY/day in import, 22.6 million JPY/day in sum) but one “Train-on-Train” terminal less that “s, k, o” scenario. If only one terminal is considered to be constructed, “o” will be the optimal location with saved cost of 6.2 million JPY/day in export case, 15.0 million JPY/day in import, and 21.2 million JPY/day in the sum.

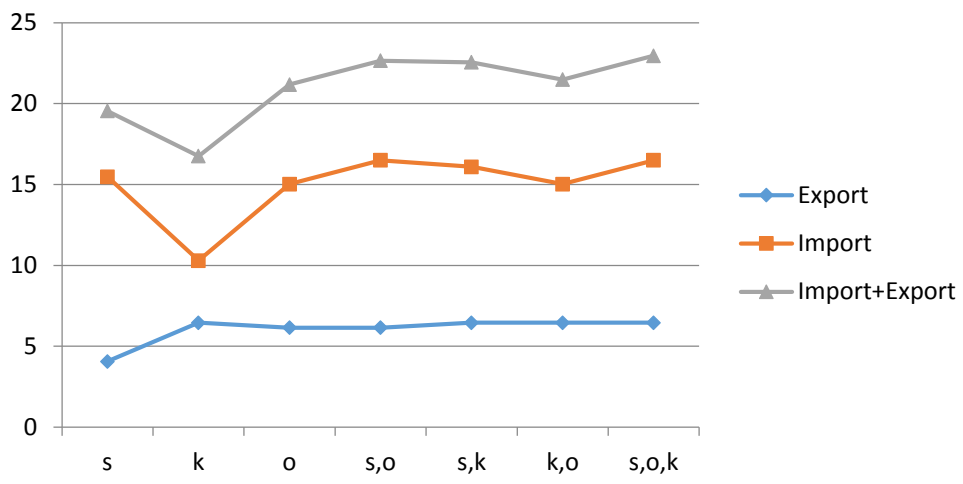

Figure 19 Saved Total Generalized Cost of High-speed Freight Railway (Million JPY/day).

According to these results, high-speed rail trains will definitely improve the efficiency of Hokkaido logistics transport network. These planning schemes are related to different construction and maintenance costs, so between these costs and high-speed railway's benefit–saved generalized cost, optimal decisions can be made based on these results. In the following vulnerability scanning section, the "s, k, o" scheme is as the optimal planning of high-speed railway network only considering the most saved generalized transport cost.

4.7 Vulnerability scanning of study network

4.7.1 Link vulnerability scanning

Dijkstra algorithm is applied in c++ program to find the shortest routes between each od pair which is one of the fundamental steps of vulnerability evaluation. These shortest routes decide the set of necessary and most efficient links connecting all od pairs. And the generalized cost of current logistics transport network C_t is calculated as the contrast parameter. Then link k is assumed failed and the total generalized cost $C_{t_{(k)}}{}'$is calculated again when its vulnerability index $V_{(k)}$ is evaluated. This procedure is conducted for each link in the links set of shortest routes between all od pairs, greatly improving the efficiency of scanning. The links outside of the shortest routes set are ignored

because $C_{t_{(k)}}{}'$ is calculated based on the shortest route and their failure will not influence the result of shortest routes searching.

From the vulnerability scanning results, every link can be clearly ranked by vulnerability index. However, thousands of link vulnerability ranks are difficult to show. So according to how much the total generalized cost of logistics transport difference (ΔC_t) increases, links vulnerability is classified to several categories. If there are od pairs disconnected caused by links failure, these links are marked by “Most critical” category. Those links are marked by “Relatively critical”, when their failure resulting in ΔC_t more than 10 million which means the logistics transport generalized cost increase by over 10 million JPY/day. Links are marked by “Critical”, when ΔC_t is between 1 million and 10 million. And “Important” is marked between 0.1 million and 1 million. If the lost is less than 0.1 million JPY/day, it seems in the acceptable range and with “Light” influence to the total cost, therefore these links together with the links out of shortest routes set are classified into “Light” category.

This link vulnerability scanning is implemented in diverse logistics demands mentioned before. Vulnerability is scanned under four different logistics traffic demand scenarios of “Export in average”, “Import in average”, “Export in September” and “Export in May”. In export scenarios, volume of logistics traffic demands levels increase from low level (May) to high level (September). There are 1058 links (17.2% of total) are in the set of shortest routes in export scenarios. In “Most critical” category, there are 28 links in every export scenario. There isn't any link classified into “Relatively critical” category in export scenarios. Link numbers increase as export logistics demand levels both in “Critical” and “Important” category, however decline in “Light” category. Import scenario has 843 links (14.2% of total) in the shortest routes set which is less than the export case. The “Most critical” category is still 28 links. The “Relatively critical” category increases by 15 links comparing to export cases. All these scanning results are shown in Table 1 and Table 2.

Table 1 Result of Link Vulnerability Scanning In Export Case

Export									
Links set	Shortest routes set (17.2%)								Others
Categories	Most critical		Relatively critical ($10<\Delta C_t$)		Critical ($1<\Delta C_t<10$)		Important ($0.1<\Delta C_t<1$)		Light ($\Delta C_t<0.1$)
	$V(k)$	No.	$V(i)$	No.	$V(k)$	No.	$V(k)$	No.	No.
May	-	28	>0.73%	0	0.073%~0.73%	5	0.0073%~0.073%	264	5885
Average	-	28	>0.43%	0	0.043%~0.43%	8	0.0043%~0.043%	382	5764
September	-	28	>0.25%	0	0.025%~0.25%	39	0.0025%~0.025%	528	5587

Note: No. = number of links; $V(k)$= vulnerability index; ΔC_t= total generalized cost difference (million JPY/day); - = not available because some origin and destination pairs are not connected.

Table 2 Result of Link Vulnerability Scanning In Import Case

Import									
Links set	Shortest routes set (14.2%)								Others
Categories	Most critical		Relatively critical ($10<\Delta C_t$)		Critical ($1<\Delta C_t<10$)		Important ($0.1<\Delta C_t<1$)		Light ($\Delta C_t<0.1$)
	$V(k)$	No.	$V(k)$	No.	$V(k)$	No.	$V(k)$	No.	No.
Average	-	28	>0.09%	15	0.009%~0.09%	60	0.0009%~0.009%	275	5804

Note: No. = number of links; $V(k)$= vulnerability index; ΔC_t= total generalized cost difference (million JPY/day); - = not available because some origin and destination pairs are not connected.

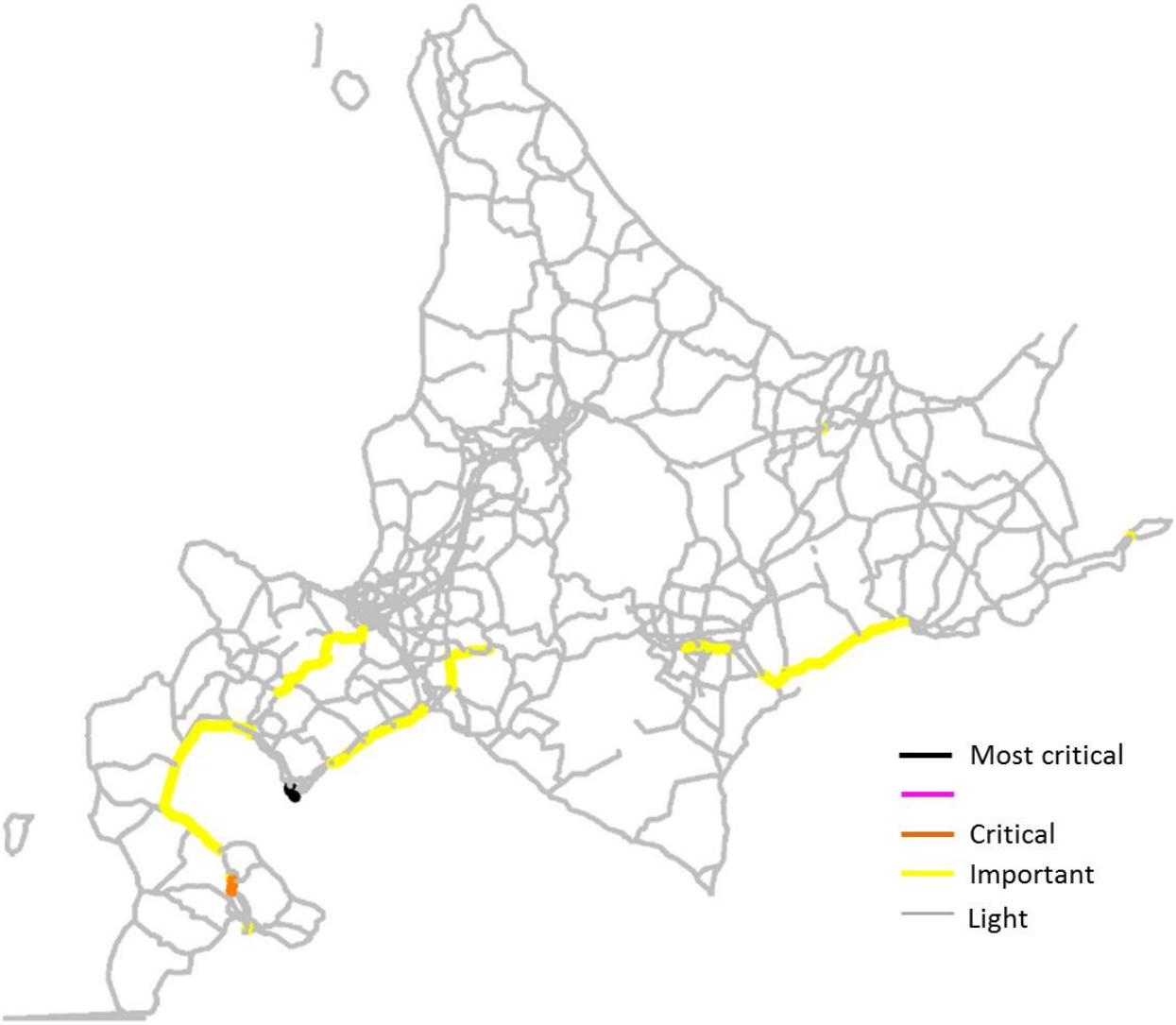

Figure 20 Link vulnerability categories in highway network (Export in May)

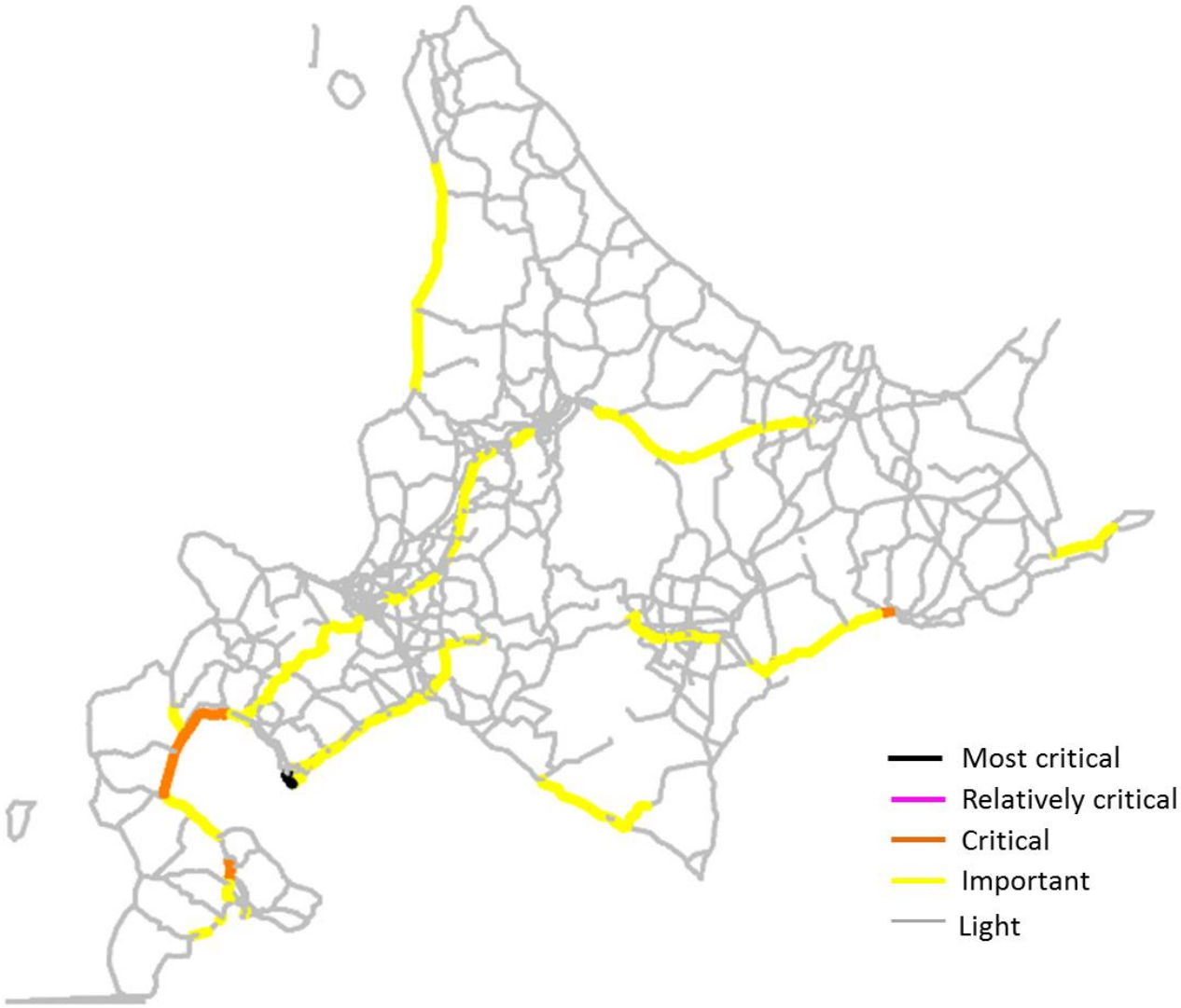

Figure 21 Link vulnerability categories in highway network (Export in September)

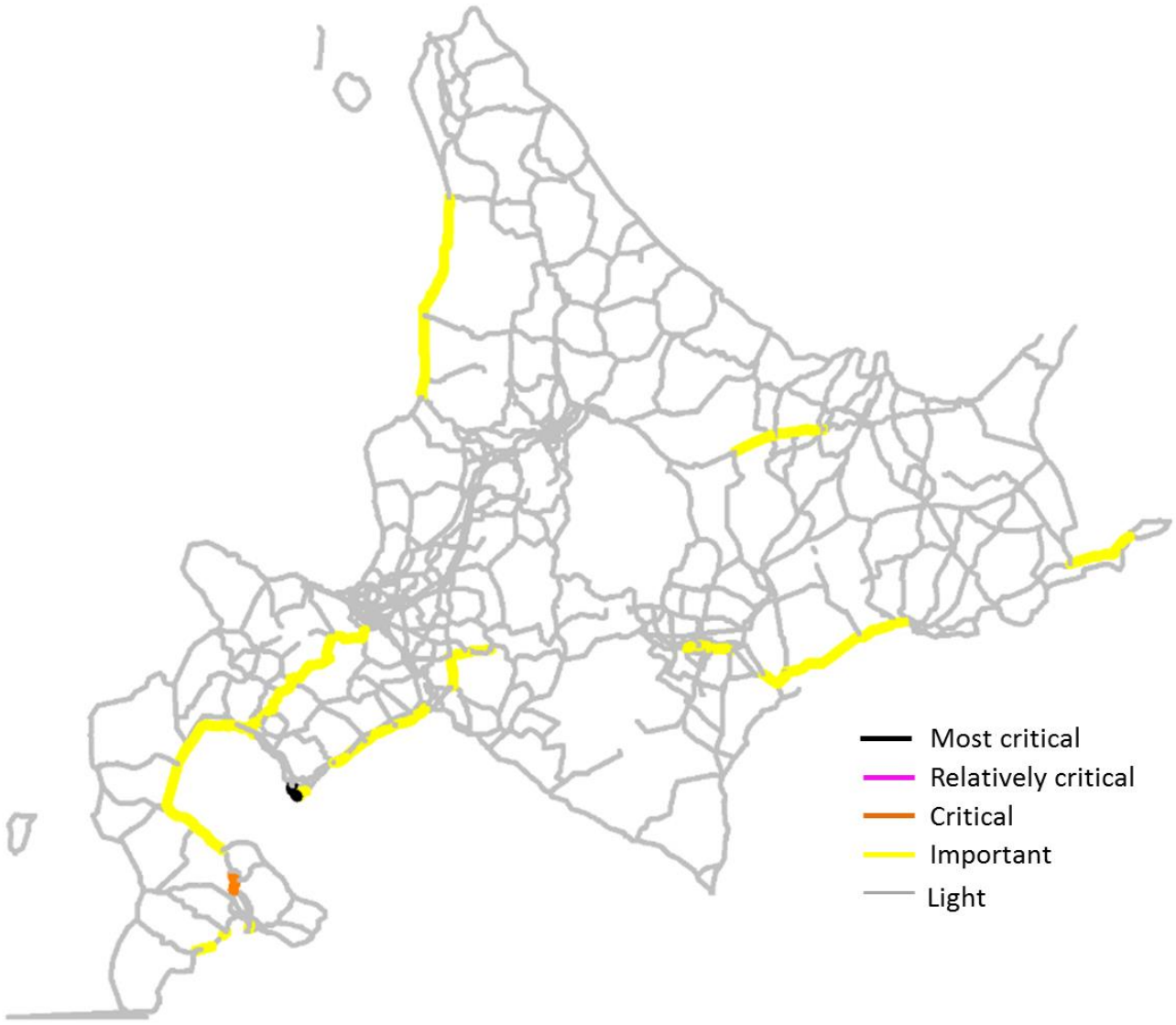

Figure 22 Link vulnerability categories in highway network (Export in average)

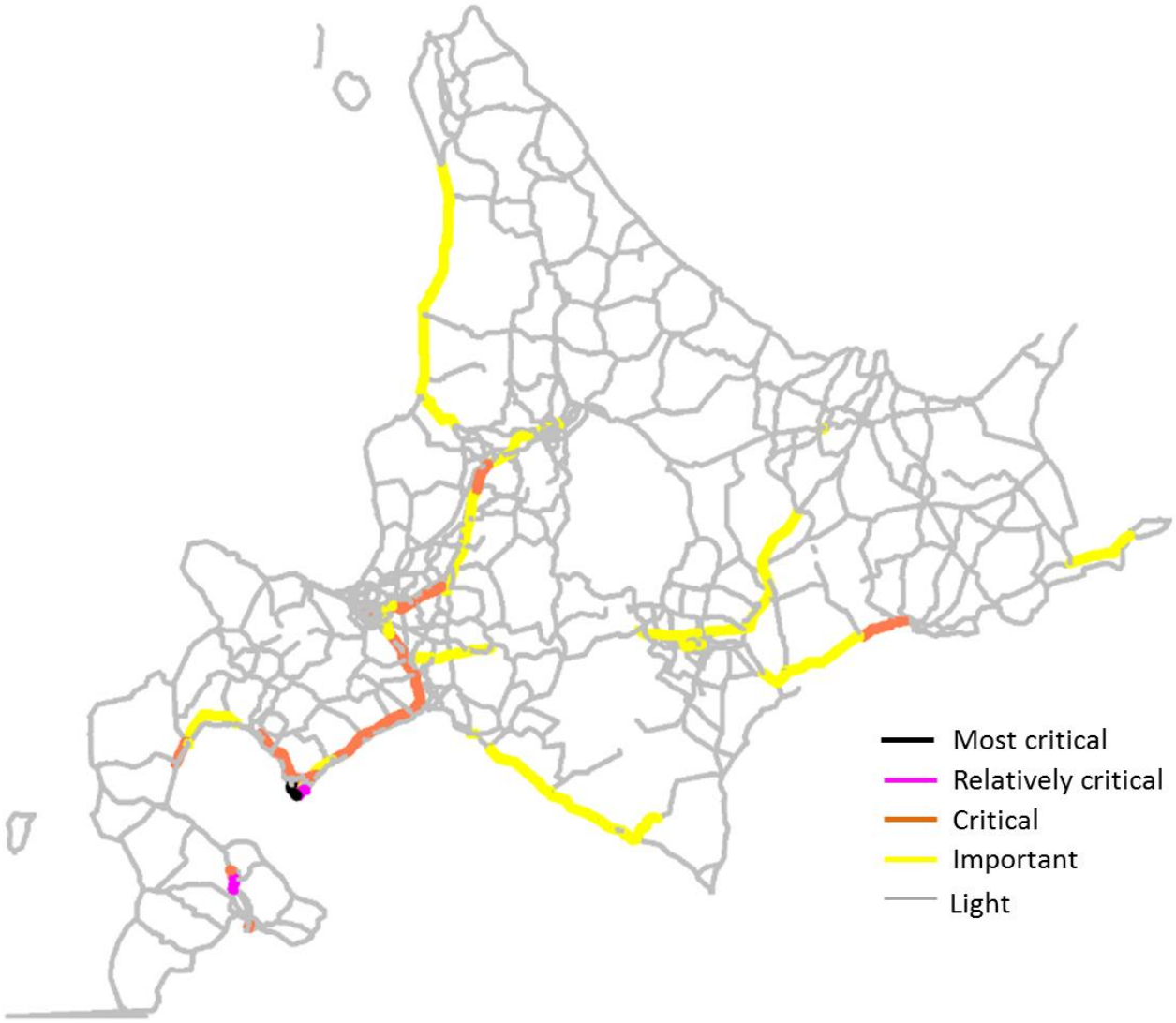

Figure 23 Link vulnerability categories in highway network (Import in average)

It should be noted that all rail and shipping links are in "Most critical" category because these links are only way connecting origin/destination in Hokkaido to rail or shipping origin/destination in Honshu. This is quite reasonable underlying the assumption of Hokkaido logistics export and import transport network. The visual results of link vulnerability categories in highway network are shown as Figure 20, Figure 21, Figure 22 and Figure 23.

4.7.2 Conclusions of link vulnerability scanning

There are 185 links less in the shortest routes set in import case than export case. That is reasonable because link impedances change as time values which are different between import and export network. The results show that the link numbers in "Most critical" category doesn't change as demand. Actually, not only the link numbers keep invariant but also the links themselves are the same group in different scenarios. These links don't have alternative links connecting od pairs, in other words, their disruption will disconnect some od pairs. These links are decided by the network topology structure and have nothing to do with traffic demands and even the impedance of links. "Critical" and "Important" categories are sensitive to logistics traffic demand levels that are shown by the comparison between Figure 20 and Figure 21. It can be explained that links' disruption will cause total logistics transport cost difference (ΔC_t) bigger and more links are included in vulnerable category when traffic demand level is higher. However, corresponding $V_{(k)}$ decrease as traffic demands. So the absolute change of the network performance (ΔC_t) can just show the category of vulnerability but $V_{(k)}$ indicates a more detailed vulnerability rank in each category.

The scenarios in export case shows vulnerability change as traffic demand levels, while Figure 22 and Figure 23 show how vulnerability responds to variation of the of traffic demand distribution. Import scenario has same link numbers in "Most critical" category still keep same as export case, which further explain that this category has no influence from traffic demands. However, link numbers in both "Critical" and "Relatively Critical" categories greatly increase comparing export case. This show that disruption of links will result in bigger lost in import logistics transport which has correspondence in real world because industrial material has (import logistics) much higher time value than agriculture products (export logistics).

4.7.3 Node vulnerability scanning

Link vulnerability scanning is proposed based on assumption that the single link disruption pattern supposing that the attacks from nature or human society only result in single link disrupted. However, the attack are usually area covering and result in several links nearby disrupted. So the node

vulnerability scanning is proposed to reflect this situation. The disruption of node representing intersection failure involving all links connected to it failed too.

Similar algorithm is applied in node vulnerability scanning. The shortest routes between all od pairs are searched at first and the nodes set of shortest routes are obtained. When the node k is disrupted, all the links connected to it will also fail and the total generalized cost ${C_{t_{(k)}}}'$is calculated again when its vulnerability index $V_{(k)}$ is evaluated. Similarly, all these procedures are conducted for each node in the set of shortest routes between all od pairs.

The node vulnerability scanning is also applied under diverse logistics demands. And same to link vulnerability scanning, nodes are classified into different categories by total generalized cost difference (ΔC_t). There are 1052 nodes (18.0% of total) in the shortest routes set in export case, and 885 nodes (15.2% of total) in import case. In every scenario, there are 22 nodes in “Most critical” category. As explained in link vulnerability scanning section, failure of these nodes will result in disconnection of some od pairs, and they have nothing to do with traffic character but topology character of network. “Relatively critical” category in export case keeps same numbers of nodes in different scenarios but node numbers increase as traffic demand in “Critical” and “Important” categories. In import case, node numbers in “Most critical” category is still 22 nodes. However, it greatly increases in “Relatively critical” and “critical” categories comparing to export case. All these results are also shown in Table 3 and Table 4.

Table 3 Result of Node Vulnerability Scanning In Export Case

Export									
Nodes set	Shortest routes set (18.0%)								Others
Categories	Most critical		Relatively critical ($10<\Delta C_t$)		Critical ($1<\Delta C_t<10$)		Important ($0.1<\Delta C_t<1$)		Light ($\Delta C_t<0.1$)
	$V(k)$	No.	$V(k)$	No.	$V(k)$	No.	$V(k)$	No.	No.
May	-	22	>0.73%	2	0.073%~0.73%	8	0.0073%~0.073%	268	5538
Average	-	22	>0.43%	2	0.043%~0.43%	14	0.0043%~0.043%	383	5417
September	-	22	>0.25%	2	0.025%~0.25%	46	0.0025%~0.025%	530	5238

Note: No. = number of nodes; $V(k)$= vulnerability index; ΔC_t= total generalized cost difference (million JPY/day); - = not available because some origin and destination pairs are not connected.

Table 4 Result of Node Vulnerability Scanning In Import Case

Import									
Nodes set	Shortest routes set (15.2%)								Others
Categories	Most critical		Relatively critical ($10<\Delta C_t$)		Critical ($1<\Delta C_t<10$)		Important ($0.1<\Delta C_t<1$)		Light ($\Delta C_t<0.1$)
	$V(k)$	No.	$V(k)$	No.	$V(k)$	No.	$V(k)$	No.	No.
Average	-	22	>0.09%	19	0.009%~0.09%	70	0.0009%~0.009%	272	5455

Note: No. = number of nodes; $V(k)$= vulnerability index; ΔC_t= total generalized cost difference (million JPY/day); - = not available because some origin and destination pairs are not connected.

4.7.4 Conclusions of node vulnerability scanning

There are same 22 nodes in “Most critical” category in both export and import case. Then these 22 nodes are not simply including nodes connected to the “Most critical” links in link

vulnerability scanning, but also other new nodes. Even though single disruption of these involved links doesn't disconnect od pairs, their combinations will do. It shows that node vulnerability can reflect network vulnerability in a different view from single link vulnerability scanning. In export case, nodes in "Critical" and "Important" categories increase as logistics traffic demands showing the same tendency as links vulnerability scanning results. Import scenario has more nodes in "Relatively critical" and "Critical" categories but almost same nodes in "Important" category comparing to export case. This shows the tendency vulnerability changes as traffic demands distributions.

4.8 Conclusions

The methodology proposed in this study is applicable to large scale and intercity logistics transport networks. Traffic congestion isn't considered when travel time is calculated, which is reasonable in an intercity logistics transport network. The static shortest path model greatly improved calculation efficiency compared with others such as the user equilibrium model. Screening the effective objects before vulnerability scanning further improves the efficiency in large scale networks. Links and nodes in the shortest routes set are both less than 20% of total links and nodes. This means a lot of the calculation is reduced in complete vulnerability scanning and allows the possibility of the methodology to be applied in real scale transportation networks. The study network includes around 6140 links and 5840 nodes and it finally takes about 7 hours to do link vulnerability scanning and 6 hours to do node vulnerability scanning in a personal computer with a Core i3 CPU @3.10GHz. Based on the structure of the C+++ program in this research, time and resource consumption will not increase in a geometrical progression as the network scales.

Logistics generalized cost is proposed to describe the link impedance in logistics transport networks. It considers both the economy value of the logistics industry and its transport value. Total generalized logistics transport cost reflects a global view in all users' benefit. It provides road network administrations assistance for benefit-cost-analysis.

Diverse logistics traffic demands including volume and distribution diversity are applied in vulnerability scanning. The results show that traffic demands evidently influence vulnerability

scanning results. Some vulnerable categories (such as “Critical” and “Important”) are more sensitive to demand volume variation. The different results between the export case and import case show that severe vulnerable category (such as “Relatively critical”) gets much more influence than light vulnerable category. Furthermore, “Most critical” category doesn’t get impacted at all by any traffic demand variation but is decided by the topology structure of the network. For links or nodes in this category, it is necessary to establish alternative links to improve resistance to network vulnerability. Generally links or nodes in severe vulnerable category should have priority to defend degradations caused by accidents or disasters.

Node vulnerability scanning methodology is also proposed besides single link vulnerability scanning. Links are usually the basic component of a network when network vulnerability is assessed, however this is not sufficient in the situation where area-covering disasters occur and result in disruptions of more than a single link. In node vulnerability scanning, node failure supposes that all links connected to it fail, too. In the intercity logistics transportation system, this hypothesis can really explain the situation when disasters such as snow storms and floods happen to a transportation hub, causing failure of all links connected to it. The results of node vulnerability scanning show us that a combination of links has different character from its individual links, and it is necessary to do vulnerability in various strategic levels. Even though consideration of node vulnerability is new from link vulnerability, it is still closely related to the links, and further discussion is needed to synthetically evaluate the vulnerability of individual links.

CHAPTER 5 SEISMIC VULNERABILITY SCANNING OF LOGISTICS TRANSPORT NETWORKS

5.1 Seismic vulnerability assessment

The losses caused by natural catastrophes has dramatically increased worldwide in the last few decades. One of the reasons for the increased losses is that the expansion of human settlements caused by increased world population especially the big cities, are located in zones of high seismic hazard (Smolka, Allmann, Hollnack, & Thrainsson, 2003). The 1994 earthquake in Northridge, California, USA, produced earthquake loss at approximately 14 billion US dollars, and the 1995 Kobe earthquake in Japan earthquake cost around 150 billion US dollars loss (Calvi et al., 2006). Although the dollar value of economic losses in other parts of the world may be far lower than in Japan and the US, the impact on the national economy may be greater due to losses being a larger proportion of the gross national product in that year. Coburn and Spence report the economic losses due to earthquakes from 1972 to 1990; the three largest losses as proportions of the gross national product (GNP) are in the central American countries of Nicaragua (1972, 40% GNP), Guatemala (1976, 18% GNP) and El Salvador (1986, 31% GNP) (Coburn & Spence, 2002). In order to design insurance and reinsurance schemes to seismic disasters, a reliable seismic disaster loss model for the region under consideration needs to be compiled such that the future losses due to earthquakes can be determined with relative accuracy.

The formulation of an earthquake loss model for a given region is not only of interest for predicting the economic impact of future earthquakes, but can also be of importance for risk mitigation. A loss model that allows the damage to the built environment and important lifelines to be predicted for a given scenario which are from the repetition of historical earthquake can be particularly important for emergency response and disaster planning by a national authority. Additionally, the model can be used to mitigate risk through the calibration of seismic codes for the design of new buildings; the additional cost in providing seismic resistance can be quantitatively

compared with the potential losses that are subsequently avoided. Furthermore, the seismic vulnerability assessment model can be used to design retrofitting schemes by carrying out cost-benefit analysis for different types of structural intervention schemes.

Earthquake loss assessment models, ideally, include all of the possible hazards from earthquakes: amplified ground shaking, landslides, liquefaction, surface fault rupture, and tsunamis. However, the existing seismic vulnerability assessment methodologies over the past 30 years mostly focus on the ground shaking damage in loss assessment methods and this is commonly an acceptable approach because as the size of the loss model increases, the relative influence of the secondary hazards such as liquefaction and landslides decreases (Bird & Bommer, 2004). Developing an earthquake loss model for a city, region or country involves compiling databases of earthquake activity, ground conditions, ground motion prediction equations, building stock and infrastructure exposure, and vulnerability characteristics of the exposed inventory. The main aim of a loss model is to calculate the seismic hazard at all the sites of interest and to convolve this hazard with the vulnerability of the exposed building stock such that the damage distribution of the building stock can be predicted; damage ratios, which relate the cost of repair and replacement to the cost of demolition and replacement of the structures, can then be used to calculate the loss.

A significant component of a loss model is a methodology to assess the vulnerability of the infrastructure environment. The seismic vulnerability of a structure can be described as its susceptibility to damage by ground shaking of a given intensity. The aim of a vulnerability assessment is to obtain the probability of a given level of damage to a given building type due to a scenario earthquake. The various methods for vulnerability assessment that have been proposed in the past for use in loss estimation can be divided into two main categories: empirical or analytical, both of which can be used in hybrid methods (Calvi et al., 2006).

Referring to this vulnerability assessment framework, this chapter proposes a seismic vulnerability assessment model for logistics transportation network. The methodology applied in chapter 4 scans the vulnerability of transportation supposing every transportation network component has the same degradation probability. The results show the vulnerable sequence by evaluating how

much damage to the whole network performance when there are partial degradations happen to the network. In this vulnerability evaluation framework, parts of a transportation network such as links and nodes are supposed degraded by any attack from either human interference or natural disaster. “Attacks” may be cyclical disruptions such as daily congestion and maintenance activities, or unexpected events such as traffic accidents, structural breakdowns, natural hazards, or even more rare events like terrorist attacks, to mention a few. It is difficult to predict the probability of these threats occurring and which part of the network will be affected. So vulnerability evaluation by quantifying the consequences of partial network degradations reflects vulnerable spots under a sure degradation situation. However, while the consequences of network degradation can show how important these degraded parts are in the whole network operation, they do not show which parts are vulnerable under a specific disaster. In practice, the probabilities of degradation between different parts, especially in large scale networks like inter-city logistics transportation networks, are quite different. Some components may have significant consequences in the event of degradation, but have very low probability of degradation occurring, so it would not be reasonable to say these parts are vulnerable. There are different approaches for resisting different threats. For example, traffic control measures can be applied to reduce threats from daily traffic congestion, and structural measures can be taken to reinforce transportation networks to resist seismic disasters. If vulnerability is evaluated under specific disasters, the results would be helpful in taking reinforcement measures to improve the network’s ability to resist that disaster.

This chapter proposes a measurement to evaluate the vulnerability of logistics transportation networks under seismic disaster considering both the consequences of network degradation and the probability of degradation. The results are expected to provide assistance for making reinforcement policy to reduce logistics transportation network vulnerability under seismic disaster. The concept of vulnerability analysis is related to evaluating the consequences of network degradation caused by incidents such as social or nature disasters. Many methodologies have been proposed to evaluate transportation network vulnerability by quantifying the consequence of partial network degradation. However, the consequence of network degradation without considering the probability of degradation

can only show how important these degraded parts are in the whole network operation, but cannot show which parts are vulnerable under a specific disaster. In fact, some parts may have large consequences by their degradation but have very low probability of degradation occurring, so it would not be reasonable to say these parts are vulnerable. Additionally, vulnerability evaluation considering only consequence but not probability of degradation is not sufficient in helping to take reinforcement measures to resist degradation because resistant measures are quite different depending on the factors resulting in network partially degradation. This study proposes a methodology to scan vulnerability of logistics transportation networks under seismic disasters. It considers both the difference caused by component degradation and also the probability of component degradation caused by seismic disaster. The results will be helpful in making reinforcement policy for resisting seismic damage. An appropriate measurement of performance specific to logistics transportation network (total generalized cost), which is different to passenger transportation network measurement, is used in this study. Finally visual results of the vulnerability evaluation of a study network are demonstrated using Geographic Information System (GIS) technology.

5.2 Seismic vulnerability scanning of logistics transport networks

5.2.1 Seismic Vulnerability Index (SVI)

This chapter proposes a seismic vulnerability index (SVI) to evaluate vulnerability of logistics transportation networks under seismic disaster. SVI considers not only the difference between normal networks and degraded networks but also the probability of network degradation caused by seismic disaster. Total generalized cost is used to assess the performance of logistics transport networks, and a comparison is made between degraded network and normal status. The difference of total generalized cost (DTGC) is used to evaluate the consequence of network degradation. DTGC represents the degradation of transportation network quantified by generalized cost of logistics transport, and P_k is the probability of component k of network disruption caused by seismic disaster. $SVI_{(k)}$ is the seismic vulnerability index of component k as shown in equation (15). In this equation, a component can be any part of a network such as a link or node or a combination like links in one

area of transportation network. the link as a typical transportation network component is an example to show how seismic vulnerability scanning is done in the following case study section.

$$SVI_{(k)} = DTGC_{(k)} \times P_k = (TGC_{(k)}{}' - TGC) \times P_k \tag{15}$$

Where,

$SVI_{(k)}$: seismic vulnerability index of component k,

$DTGC_{(k)}$: difference of total logistics transport cost when component k degrades,

TGC total generalized cost of logistics transportation in the normal status,

$TGC_{(k)}{}'$: total generalized cost of logistics transportation after component k degrades,

P_k: Probability of degradation of component k caused by seismic disaster.

5.2.2 Total generalized cost of intermodal logistics transportation network

The logistics transport demands are also considered here to evaluate the performance of the whole network. The least generalized cost between origin (o) to destination (d) denoted as $C_{g(od)}$, is the sum cost of links in the least generalized cost path between od pair as shown in equation (16). In the following study network, the Dijsktra algorithm is used to search the shortest path, which greatly improves the computing efficiency. Then the total generalized cost (TGC) of all od pairs are calculated based on $C_{g(od)}$ and the logistics travel demands of each od pair as shown in equation (17). The total generalized cost is used to evaluate the performance of the logistics transportation network.

$$C_{g(od)} = \sum_{S} C_{g(i)} \tag{16}$$

Where,

$C_{g(od)}$: generalized cost of logistics transported between od pair,

$C_{g(i)}$: generalized cost of link i,

S: set of links in the least generalized cost path between od pair.

$$\mathrm{TGC} = \sum_{od}^{OD} (C_{g(od)} \times d_{od}) \tag{17}$$

Where,

TGC: total generalized cost of logistics transportation,

od: od pair,

OD: set of all od pairs,

$C_{g(od)}$: generalized cost of logistics transported between od pair,

d_{od}: logistics traffic demands between od pair.

Neither travel time nor travel cost is considered separately as the only factor by logistics transportation network users. Hence, any model or procedure developed to evaluate the performance of the logistics transport network must seek a trade-off between travel cost and time saving benefit. This study uses the generalized cost to evaluate the performance of logistics transportation network proposed by Du et al. (Du, Aiura, Nakatsuji, & Kishi, 2014). The generalized cost C_g includes travel cost and travel time which are connected by the time value multiplier as shown in equation (18). Travel cost is based on monetary cost such as fuel consumption, labour payment and toll fare and payment to rail companies. Travel time is based on average speed and link length.

$$C_{g(i)} = C_{(i)} + T_{(i)} \times \alpha \tag{18}$$

Where,

$C_{g(i)}$: generalized cost of logistics transport in link i,

$C_{(i)}$: monetary cost of logistics transport in link i,

$T_{(i)}$: logistics travel time in link i,

α: time value multiplier.

The monetary costs includes fuel consumption, driver payment and tolls in a highway network, and cargo payment railway networks which are most factors when network users make route choice decision. These costs are denoted by $C_{(i)}$ meaning how much the user has to pay for using link i. Travel time is another important factor impacting a logistics transport network user's route decision. The value of travel in a transport system mostly depends on the types of load it serves. For example, the more time sensitive and the more valuable the loads are, the higher the time values of their transport. Considering the character of logistics, time value cost is decided by travel time $T_{(i)}$ and time value multiplier α which depends on load type. It needs to be further noted that $C_{g(i)}$ in this study is transport cost per unit logistics which is convenient to quantify the logistics transport cost considering logistics transport volume.

In modern multi-mode logistics transportation, travel cost and travel time vary as transportation mode varies because travel speed and charge rules depend on transportation mode. In this study, only highway and railway transport modes are included, but the methodology could be extended to include other modes. In highway logistics transport networks, trucks are usually popular vehicles, so these are considered in this study. To get average travel cost in the highway network, one standard vehicle capacity is assumed for convenience in simulation. For one standard vehicle's single trip, the logistics transport cost and time is mostly related to transport distance. Link travel time $T_{h(i)}$ is calculated by the link length l_i and average speed in this link v_i as shown in equation (19). Link travel cost $C_{h(i)}$ consists of fuel consumption, toll and labour cost as shown in equation (20).

$$T_{h(i)} = \frac{l_i}{v_i} \tag{19}$$

Where,

$T_{h(i)}$: travel time of highway link i,

l_i: length of highway link i,

v_i: average speed in highway link i.

$$C_{h(i)} = l_i \times f + To_i + T_{h(i)} \times p \tag{20}$$

Where,

$C_{h(i)}$: monetary cost of logistics transport of highway link i,

l_i: length of highway link i,

f: fuel consumption per kilometre,

To_i: toll of highway link i (in case that i is charged link),

$T_{h(i)}$: travel time of highway link i,

p: driver's payment per hour.

Different from highway network, links in railway network are not only topological connections between two nodes but also are decided by train schedules. Actually railway routes are more complicated than only connections between two freight stations but also depend on train classes, for example, some trains do not stop at some stations and can't load or unload in others. These schedules are decided by rail companies and are flexible. It is difficult to simulate all these train schedules and this study aims to evaluate vulnerability of logistics transport network under seismic disaster which is the least guarantee of logistics transportation, so the real train schedules are not used in this study. However, the physical connections between each freight station will be the least guarantee for logistics transportation. In this study, rail links are supposed to be physical connections between each two freight stations, and travel time is not only simply related to distance but also freight train stop time in the freight stations. Average travel speed and average load fare for unit distance and unit load are used to get travel time and travel cost in rail links as shown in equation (21)

and (22). In this study, average travel speed, average load fare and average train stop time at each station are decided referring to local data of the study network.

$$T_{r(ij)} = \frac{l_{ij}}{v_{ij}} + t_{ij} \tag{21}$$

Where,

$T_{r(ij)}$: travel time in railway link ij (physical connection between station i and j),

l_{ij}: length of railway link ij,

v_{ij}: average speed in railway link ij,

t_{ij}: average train stop time in station i and j.

$$C_{r(ij)} = f_{ij} \times l_{ij} \tag{22}$$

Where,

$C_{r(ij)}$: monetary cost of logistics transport in railway link ij,

f_{ij}: average load fare in railway link ij,

l_{ij}: length of railway link ij.

5.2.3 Seismic vulnerability scanning algorithm

Seismic vulnerability scanning is conducted based on the performance evaluation of a transport network. Firstly, based on the shortest path, the total generalized cost TGC is calculated as the contrast from normal status to a degraded condition. Then the link k's capacity will be degraded to be 0 and the total generalized cost $TGC_{(k)}{}'$is calculated again when its vulnerability index $SVI_{(k)}$ is evaluated. This procedure is conducted for each link in the links set of shortest routes between all od pairs. The links outside of the shortest routes set are not necessary to do the calculation because $TGC_{(k)}{}'$ is calculated based on the shortest route and their degradation will not influence the result of shortest routes searching. This efficient algorithm can finish the links vulnerability scanning in a reasonable time period. $SVI_{(k)}$ is calculated for every component in the network which is called

seismic vulnerability scanning. The algorithm of seismic vulnerability scanning is as shown as in Figure 24. Based on the results of seismic vulnerability scanning, all components are ranked by $SVI_{(k)}$. The higher $SVI_{(k)}$ rank is, the more vulnerable the component is under seismic disasters.

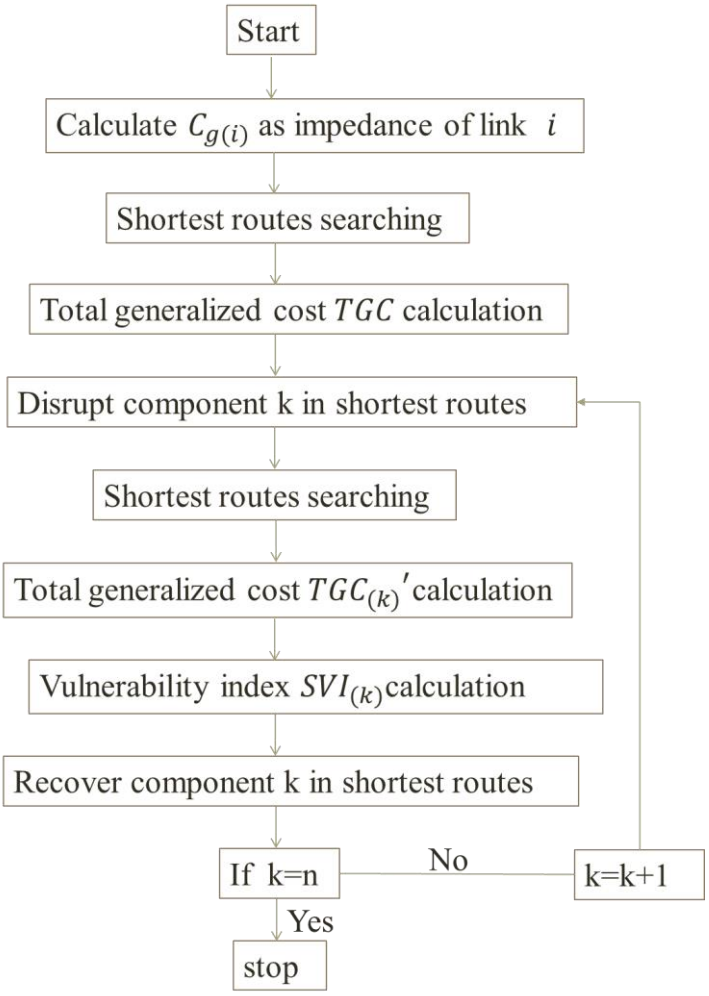

Figure 24 Seismic vulnerability scanning algorithm

5.3 Probability of transportation network degradation caused by seismic disaster

Seismic hazard prediction has been researched for more than 100 years (Geller R.,1997), and there are extensive theories about prediction of earthquake all over the world. In earthquake active regions like Japan, urban and transportation planning takes into account the probability of seismic disasters. There is also a lot of related research into finding the relationship between infrastructure

damage and seismic hazard intensity (Maruyama Y., 2010, Maruyama Y., 2000). These related research subjects provide important information for determining a reasonable probability of transportation network degradation by seismic disaster.

In this study, it is assumed that links in transportation networks will de damaged by ground motion in earthquakes when the earthquake motion reaches to a certain intensity. The probabilities of link disruption are determined by the probability of destructive seismic disaster occurring to the region where these links are located. The exceedance probability of seismic hazards, is the probability of seismic disaster over a specific intensity in certain years. The probability of transportation network degradation by seismic disaster in a certain period can be deduced by this exceedance probability.

5.4 Study network

Seismic vulnerability index has been applied to assess a study network seismic disasters, which is Hokkaido logistics transportation network. Inhabitants OF Hokkaido make up only 4.3% of the Japanese population, so most local agriculture products have to be transported out of Hokkaido which is simply called “export”. On the other hand, most industrial products like commodities need to be imported from industrialized regions of Japan like Honshu which is simply called “import”. These products are mainly Hokkaido logistics, so the logistics transportation network between Hokkaido and Honshu is strategically important. However, Hokkaido is an earthquake active region and destructive earthquakes occur regularly, such as the 1952 Tokachi-Oki Earthquake and the 1993 Hokkaido Nansei-Oki Earthquake. The damage caused by these earthquakes resulted both from ground motion and tsunami. Given this high frequency of seismic disaster and the importance of logistics in modern society, it is necessary to identify the vulnerable sections in the logistics transportation network under seismic disaster.

Hokkaido is divided into 14 subprefectures shown as Figure 25. These 14 subprefectures are both agriculture product origins and industrial product destinations.

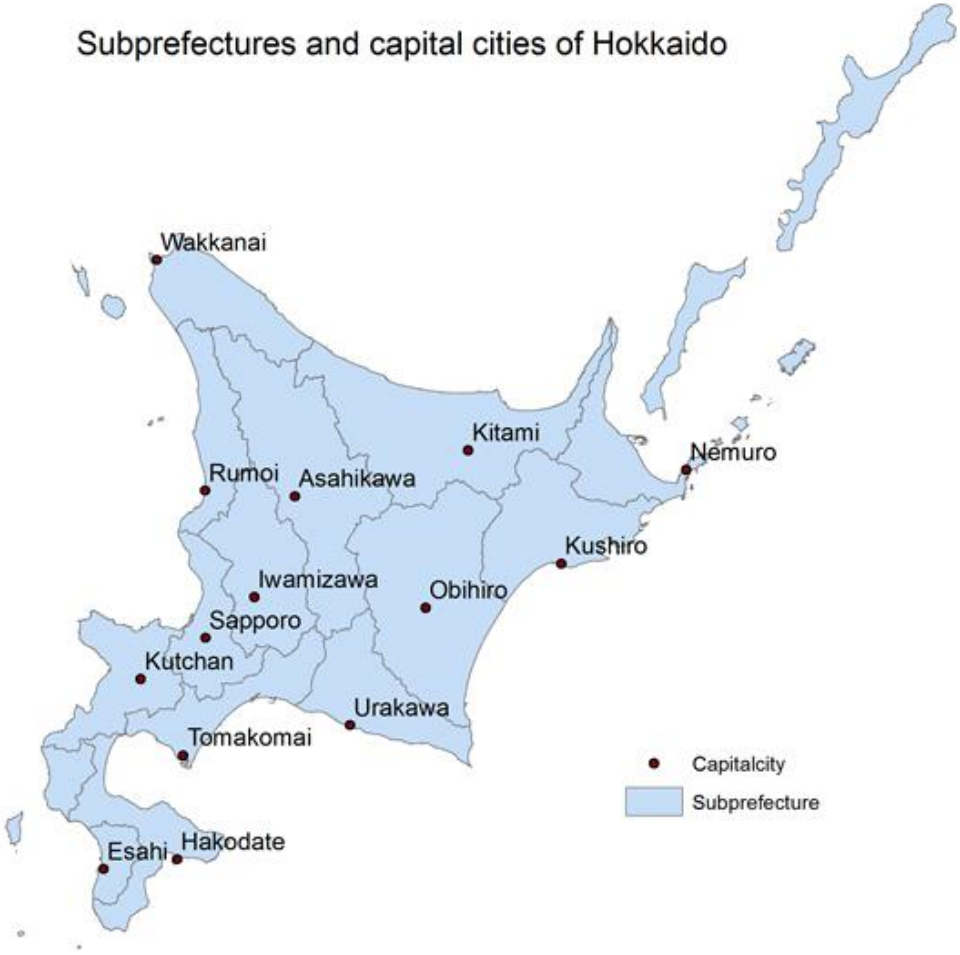

Figure 25 Subprefectures of Hokkaido

For Hokkaido logistics transportation in this study network, all capital cities of these subprefectures are supposed to be origins of agriculture products and destinations of industrial product inside of Hokkaido. The nearest big freight rail station between Hokkaido and Honshu, Aomori Station, is supposed to be the origin and destination (od) outside of Hokkaido. Logistics transportation between Hokkaido and Honshu consists of one rail tunnel, several shipping routes and airlines. To

simplify the analysis, this study focuses on the logistics between Hokkaido and Honshu by railway. The study network consists of the highways and railways shown in Figure 26.

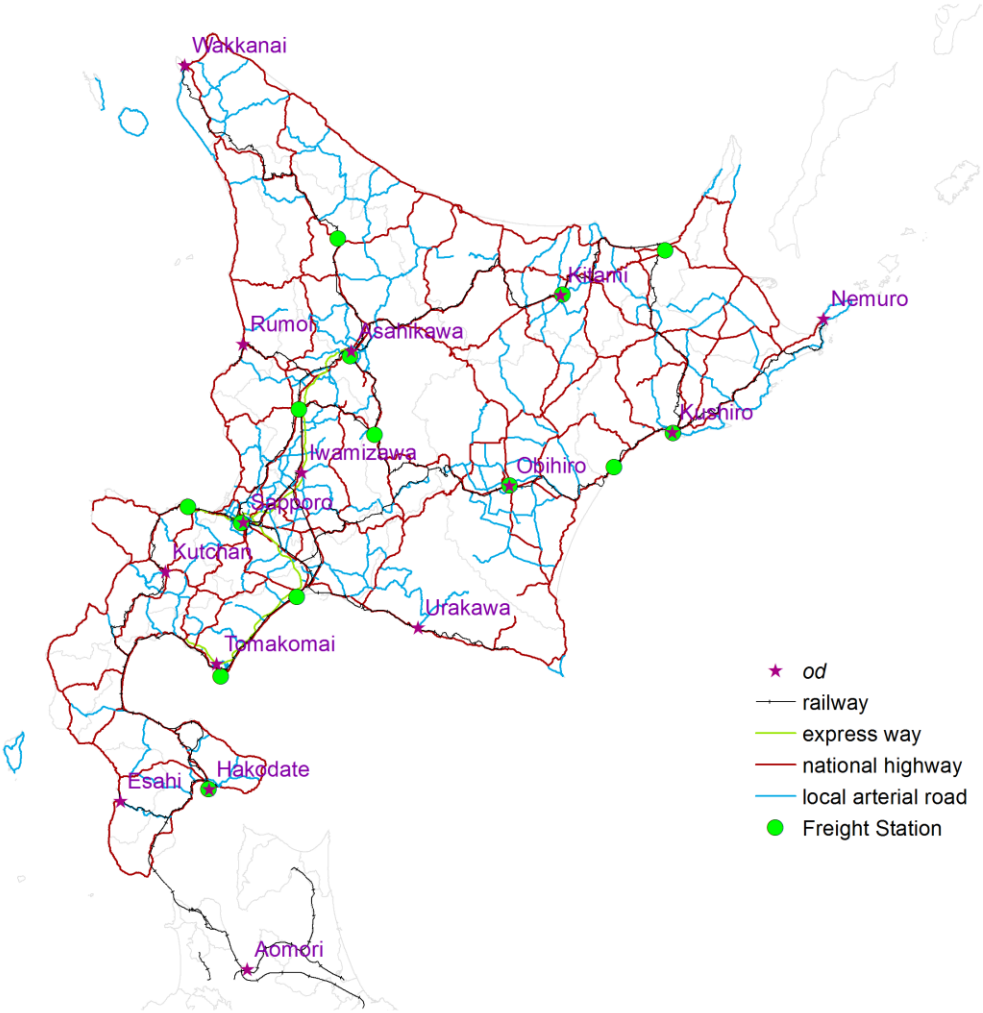

Figure 26 Hokkaido logistics transportation network

All the od pairs are also shown in Figure 26. This logistics transportation network consists of about 300 km express highway, 6000 km national highway, 4000 km prefecture arterial highway, and 3000 km railway. The highway network and railway network are joined by 14 freight stations in Hokkaido logistics transportation network and their locations are shown in Figure 26.

Logistics traffic demands are divided into two directions in this study. One is logistics volumes transported out of Hokkaido into to Honshu which are mostly agriculture products named simply "export" in the following, and the other direction is logistics volume transported into Hokkaido from Honshu which is simply named "import" in the following. The export logistics volume is based on a survey report about agriculture and livestock products exported from Hokkaido which is conducted by Hokkaido regional development bureau in 2012. The import logistics volume is based on a survey about logistics volume movement inter-region in Japan. This survey was conducted by Ministry of Land, Infrastructure, Transport and Tourism of Japan in 2011 and include railway, truck and shipping transport modes covering all prefectures and subprefectures in Japan. The logistics volumes between Hokkaido and Honshu are shown as Figure 27.

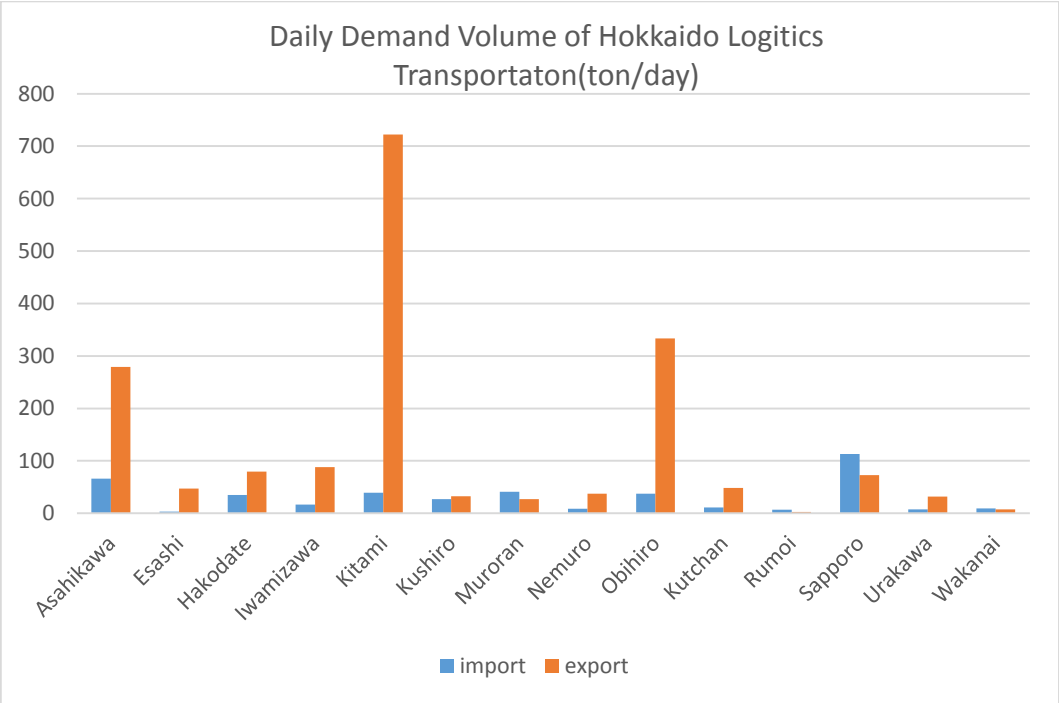

Figure 27 Logistics transport demands between Hokkaido and Honshu

According to related research, slight damage will happen to highway embankments in Japan when the JMA seismic intensity becomes lager than 4.8, and destructive damage will happen when the seismic intensity is over 5.3 (Maruyama, Y.,2010) (JMA seismic intensity refers to the scale that

the Japan Meteorological Agency specifies in classifying seismic ground motion. JMA seismic intensity scales run from 0 to7). Major damage can be found in bridges when JMA seismic intensity is larger than 4.8 (Tanaka, S.,2000). JMA intensity 5 is supposed to be the critical intensity for highway road network link disruption. The probability that a seismic disaster over JMA intensity 5 occurs in a 30 year period in Hokkaido is shown as Figure 28. In this figure, different colours show the probabilities occurring to a mesh square of size 250×250 meters.

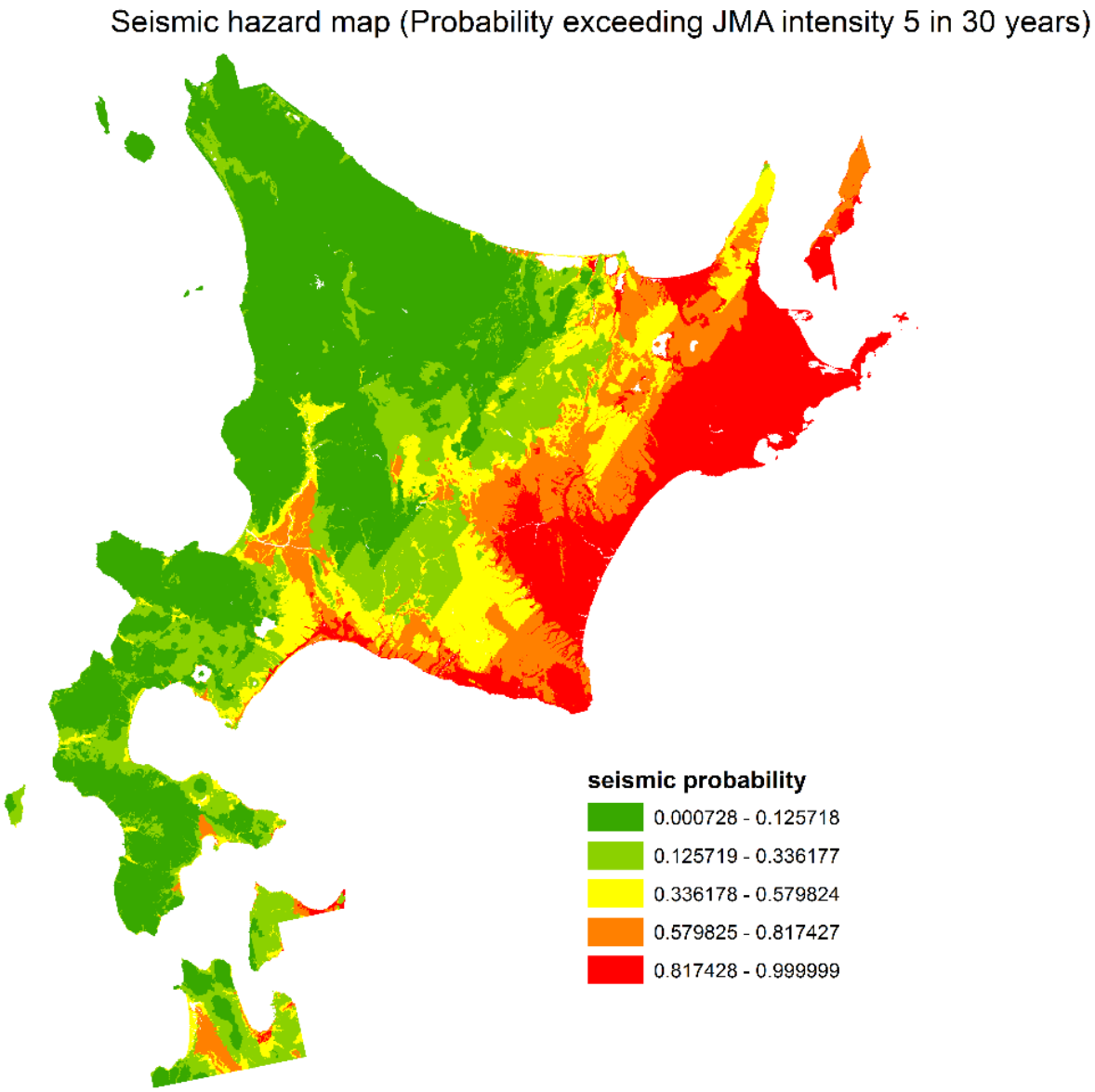

Figure 28 Seismic disaster map

The links of Hokkaido logistics transportation network are supposed to be disrupted when the earthquake intensity over JMA intensity 5. Under this hypothesis, the probability of transportation network degradation caused by seismic disasters are estimated based on the predicted seismic disasters. The transportation network of Hokkaido logistics transportation is over lapped the seismic disaster map and the predicted probability of seismic disaster occurring to each link of transportation network is estimated. If there are more than one mesh squares overlap on one link, the highest probability is used as the link disruption probability in the flowing study. As Figure 29 shows, when one link (link a) overlaps with several mesh squares, the highest seismic disaster probability (0.9) is as the probability of link a disruption by seismic disaster.

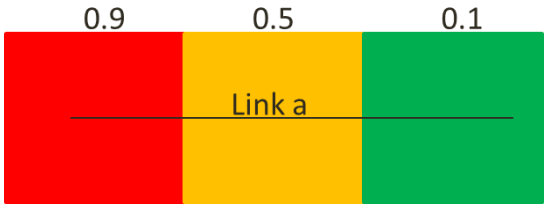

Figure 29 Probability of link disruption

And results are shown as Figure 29 which also present this predicted disruption probability of links in Hokkaido logistics transportation networks by seismic disasters.

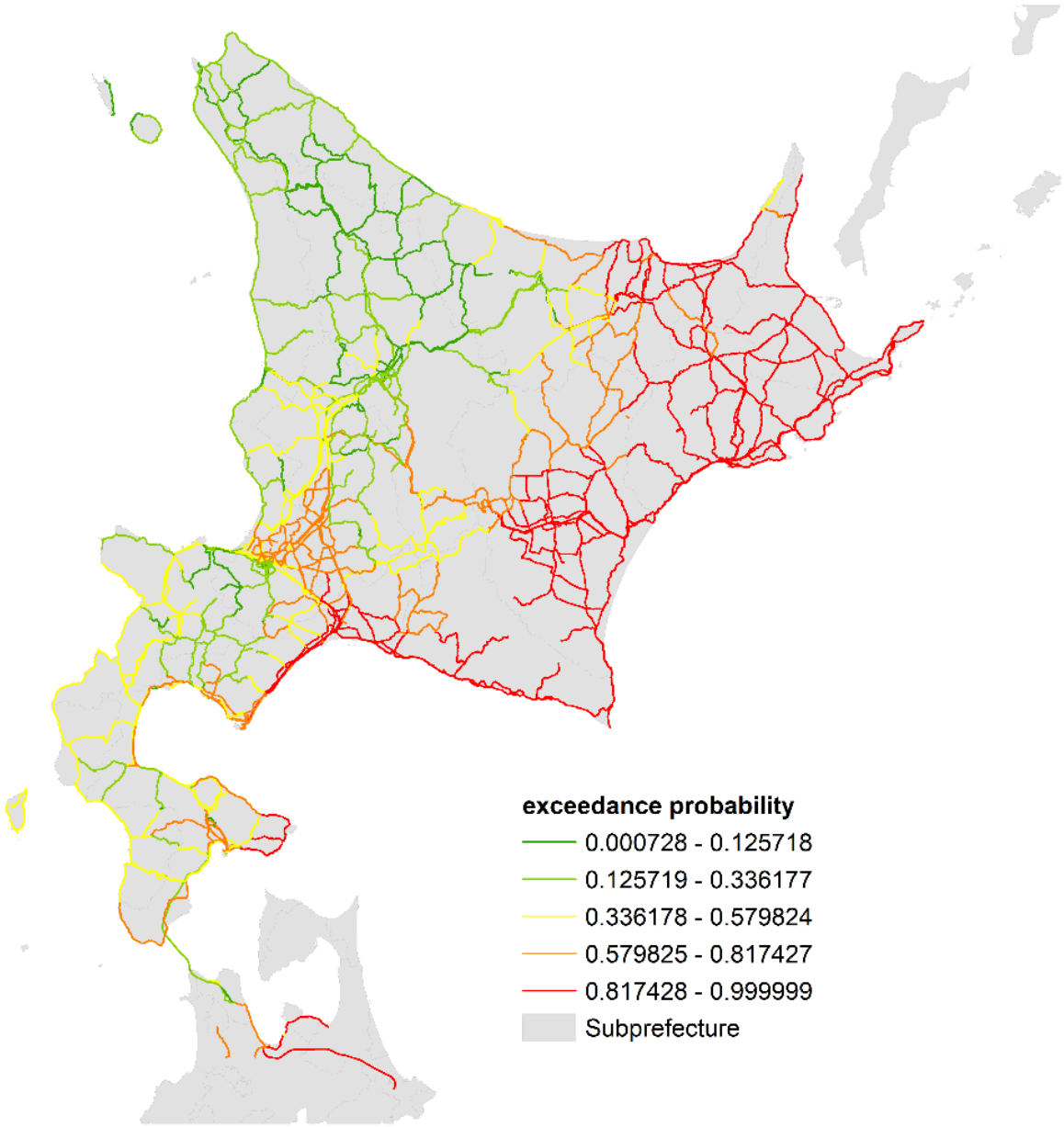

Figure 30 Seismic disaster probability of Hokkaido logistics transportation network (JAM intensity≥5)

Researchers have pointed out that the vulnerability of transportation networks show different results as traffic demands increase (Ukkusuri, S. V., 2009). In the following case study section, vulnerability scanning is conducted under both export and import logistics transport demand volumes shown as Figure 27. It should be noted that time values vary with load types. According to related research of time values (Murata, Y.,2006) in the logistics industry in Japan, the time value multiplier

α of agricultural products and other food is 240 JPY/hour which is main export logistics load, and 3240 JPY/hour of industrial products which is main import logistics load. The standard vehicle capacity is assumed to be 15 tons, according to the average capacity of popular trucks used in Hokkaido logistics transportation. The unit of travel cost is JPY/ton, the unit of travel time is the hour, the unit of the generalized cost unit is JPY/ton, and the unit of total generalized cost unit is JPY.

5.5 Simulation tools

To analyse the spatial relationships of transportation networks, a geographic information system (GIS) software is applied to describe the topological features in transportation system in this study.

A geographic information system (GIS) is a computer system designed to capture, analyse, manage, and present spatial or geographical data. The acronym GIS is sometimes used for geographical information science or geospatial information studies to refer to the academic discipline or career of working with geographic information systems and is a large domain within the broader academic discipline of geographic information science (Kenneth, 2011). GIS is one of many information technologies that have transformed the ways geographers conduct research and contribute to society. In the past two decades, these information technologies have had tremendous effects on research techniques specific to geography, as well as on the general ways in which scientists and scholars communicate and collaborate.

GIS provide powerful tools for addressing geographical and environmental issues. The following is a study case explained by Kenneth (Kenneth, 2011). Shown as the following Figure 31, a set of maps that will be helpful for urban transportation planning have been gathered. Each of these separate thematic maps is referred to as a layer, coverage, or level. And each layer has been carefully overlaid on the others so that every location is precisely matched to its corresponding locations on all the other maps. The bottom layer of this diagram is the most important, for it represents the grid of a locational reference system such as latitude and longitude to which all the maps have been precisely registered. Once these maps have been registered carefully within a common locational reference

system, information displayed on the different layers can be compared and analysed in combination. Transit routes can be compared to the location of shopping malls, population density to centres of employment. In addition, single locations or areas can be separated from surrounding locations, as in the diagram below, by simply cutting all the layers of the desired location from the larger map.

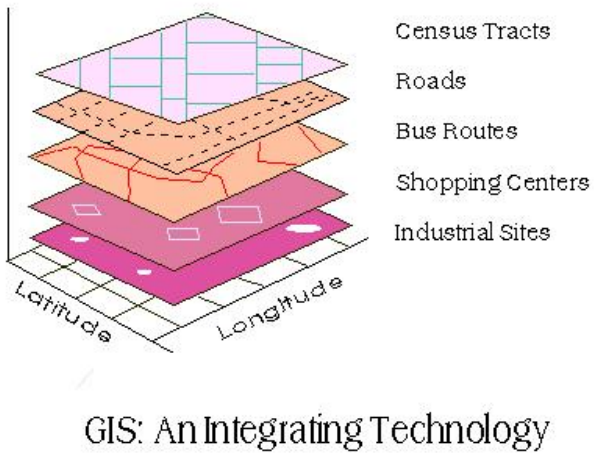

Figure 31 integrating technology of GIS (source: Kenneth E.)

The great appeal of GIS stems from their ability to integrate great quantities of information about the environment and to provide a powerful repertoire of analytical tools to explore this data. The example above displayed only a few map layers pertaining to urban transportation planning. The layers included would be very different if the application involved modelling the habitat of an endangered species or the environmental consequences of leakage from a hazardous materials site.

GIS are now used extensively in government, business, and research for a wide range of applications including urban planning, hazards management, emergency planning, or transportation forecasting, and so on.

Additionally, C++ is used in this study to make a program to calculate total generalized cost of the network, realize shortest path searching and all other procedures in seismic vulnerability

scanning. It is a powerful and efficient tool to satisfy time and computation resources of analysis for large scale networks.

5.6 Data resource

The transportation network including highway and railway data of Hokkaido is from form National land Numerical Information. The National Land Numerical Information represents numerical data prepared from information related to the national lands to support the promotion and formulation of land planning such as the Comprehensive National Development Plan, National Land Use Planning, and National Spatial Strategy. A Project to Construct National Land Information System that includes the development and use of basic information related to the national lands was started at the same time as the inauguration of the National Land Agency in 1974 to develop data to form the foundation for the creation of the Comprehensive National Development Plan. The National Land Numerical Information is digitized geographic information on topography, land use, public facilities, roads, railroads and other land-related information developed during the project to develop National Land Information System. Grid cell (meshed) data forms much of the data which can be combined with population and other statistical data to conduct analyses. In particular, information related to land has been organized chronologically and studies on annual changes and the like can be conducted.

At first, this information was freely lent out to public facilities (government institutions, local government sectors, universities, etc.). However, the information was made available over the internet for free from April, 2001 for wider dissemination. The National Land Numerical Information is divided into the following categories. Designated Regional Area includes the 3 major metropolitan planning areas, city area, agricultural areas, forest areas, etc. Coastal Zones includes fishery ports, tidal and marine facilities, coastal zone mesh, etc. Nature includes altitude and gradient tertiary mesh, land classification mesh, climatic data mesh, etc. Land Related includes publication of land prices, prefectural land price surveys, land use tertiary mesh, etc. National Land Skeleton data includes administrative divisions, coastal lines, lakes, rivers, railways, airports, ports, etc. Facilities includes public facilities, power stations, cultural assets, etc. Census of Commerce includes census of commerce mesh, census of manufacture mesh, census of agriculture mesh, etc. Hydrology includes

basin and non-water catchment area mesh, etc. The railway networks (2011), highway networks (2011), and administrative area (2012), are used in this study.

The links data in highway and railway networks is based on numerical data of road and railway sections of Hokkaido, which is digitized geographic information on topography. The link information include link name, link category, nodes of link, and length of link in highway network. Link name is the name of road, and link category is divided in to 4 according its function (expressway, national highway, prefecture arterial road, and prefecture subsidiary road). Length of link is the travel distance on the link which is measured by kilometre. Nodes of link are identification number of nodes connected with the link which will be used in programing for network analysis. Average speed is assumed according to link types in which 75km/h is average speed in expressway, 45 km/h in national highway, 35 km/h in prefecture arterial road and 30km/h in prefecture subsidiary road.

The railway networks data got from the GIS numerical including travel distances between each freight station, travel cost, and train schedules are based on the documents released from Hokkaido freight railway companies and maritime companies which charge all rail and maritime freight transportation in Hokkaido. The travel time is based on train and shipping schedules, and travel cost is based on goods transport fare by railway and shipping. There are 10 main freight rail stations and 3 maritime ports connecting highway networks, railway networks, and shipping networks together.

The seismic disaster data is form National Seismic Hazard Maps for Japan. The National Seismic Hazard Maps for Japan is prepared by a governmental organization, the Headquarters for Earthquake Research Promotion (HERP) to estimate strong motions caused by earthquakes that could occur in Japan in the future and show the estimated results on the maps. The National Seismic Hazard Maps for Japan consist of two types of maps different in nature: the Probabilistic Seismic Hazard Maps (PSHM) that combine long-term probabilistic evaluations of earthquake occurrence and strong motion evaluation, and the Seismic Hazard Maps for Specified Seismic Source Faults (also referred to as Scenario Earthquake Shaking Maps (SESM)), which are based on strong motion evaluation for scenarios assumed for specific earthquakes.

Probabilistic Seismic Hazard Maps (PSHM) are prepared by calculating the probability that a given site will experience ground motion intensity exceeding a certain value within a target period. For this calculation, evaluation is conducted by using a probabilistic approach on the site of occurrence, probability of occurrence, and magnitude of all earthquakes that could occur in and around Japan, and the intensity of the ground motions caused by those earthquakes are evaluated with variance. Seismic hazard evaluation is conducted for each site and by fixing any two parameters of the ground motion intensity, period, and probability, the value of the remaining parameter is obtained. PSHM show the distribution of such values.

There are various types of maps in PSHM. One representative is a map showing the probability that each site will be affected by an earthquake of seismic intensity 6 lower or more within 30 years shown as Figure 32.

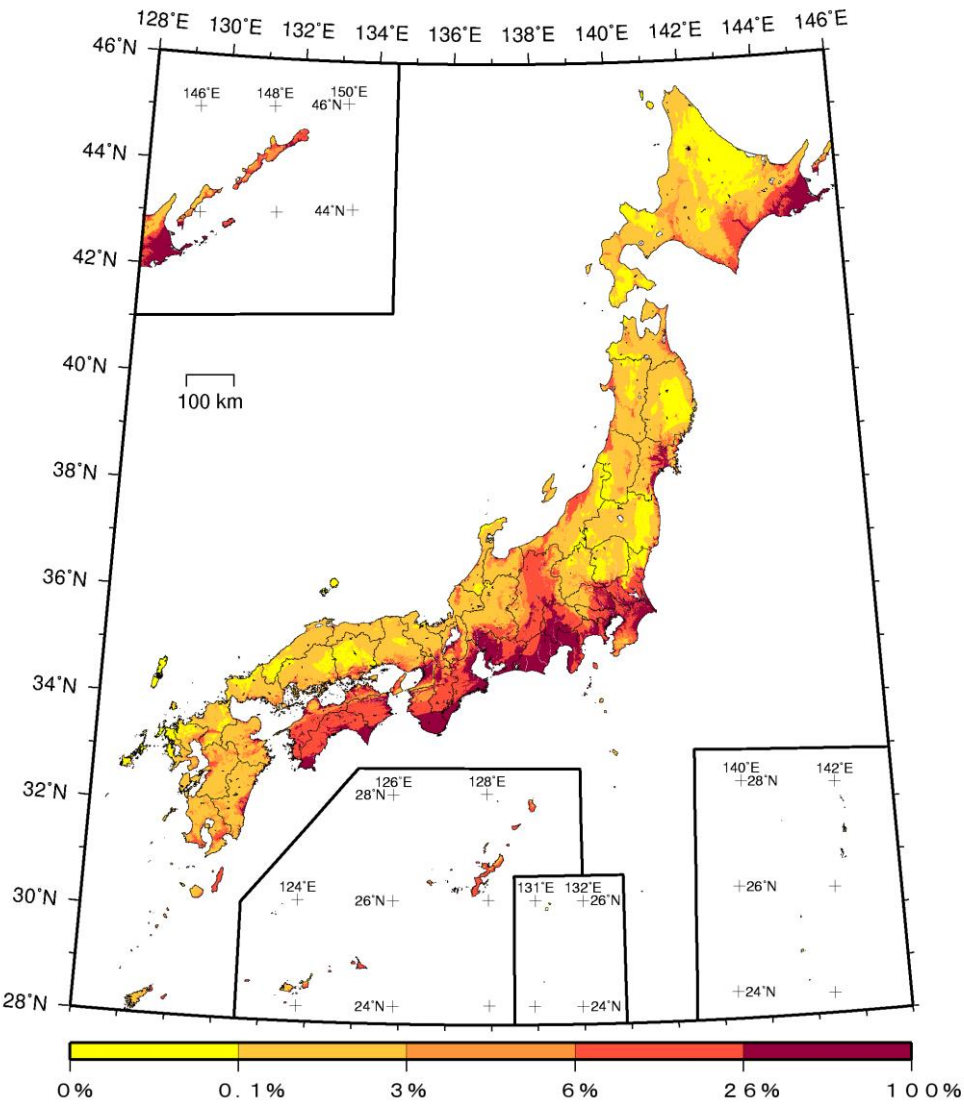

Figure 32 Exceedance probability within 30 years considering all earthquakes (JMA seismic intensity: 6 Lower or more; average case; period starting Jan. 2010)

The exceedance probability refers to the probability that shakes will exceed a certain level of intensity at a point for a certain time period (over the next 30 or 50 years, in this guidebook).For example, the "Map of ground motions of JMA Seismic intensity for a 3% exceedance probability occurring within 30 years from the present" means the probability that each point is affected by shakes exceeding its JMA seismic intensity shown on the map is 3% within 30 years from the present. JMA Seismic intensity refers to the scale that the Japan Meteorological Agency specifies in

classifying seismic ground motions. JMA seismic intensity scale runs from zero to seven. Because seismic intensities 5 and 6 involve a wide degree of damage, each of them is divided into "Lower" and "Upper." Accordingly, the JMA Seismic intensity is currently expanded to a total 10 scales.

Meanwhile, for earthquakes that occur at specified fault zones, Scenario Earthquake Shaking Maps (SESM) are designed to estimate the ground motion intensity around the faults at the occurrence of the earthquake and show the results on the maps. SESM have enabled accurate estimation of near-fault strong motions by simulating seismic wave propagation considering complex subsurface structure based on a physics model of fault rupture. Although the estimation methods used here are very complicated, the strong ground motion estimation method (Recipe) for earthquakes with specified source faults has been developed as a result of standardizing the methods.

5.7 Seismic vulnerability scanning in study network

5.7.1 The shorted path searching

The study network includes 1167 links and 863 nodes in the highway network, and 193 links and 154 nodes in railway network. Assuming that the traffic in Hokkaido logistics transportation network is free flow, Dijkstra algorithm is applied by c++ program to find the shortest route between each od pair which is one of the fundamental steps of vulnerability evaluation. In the link vulnerability scanning, the shortest routes between all od pairs are searched at first. And Figure 33 and Figure 34 show the shortest path routes between all od pairs.

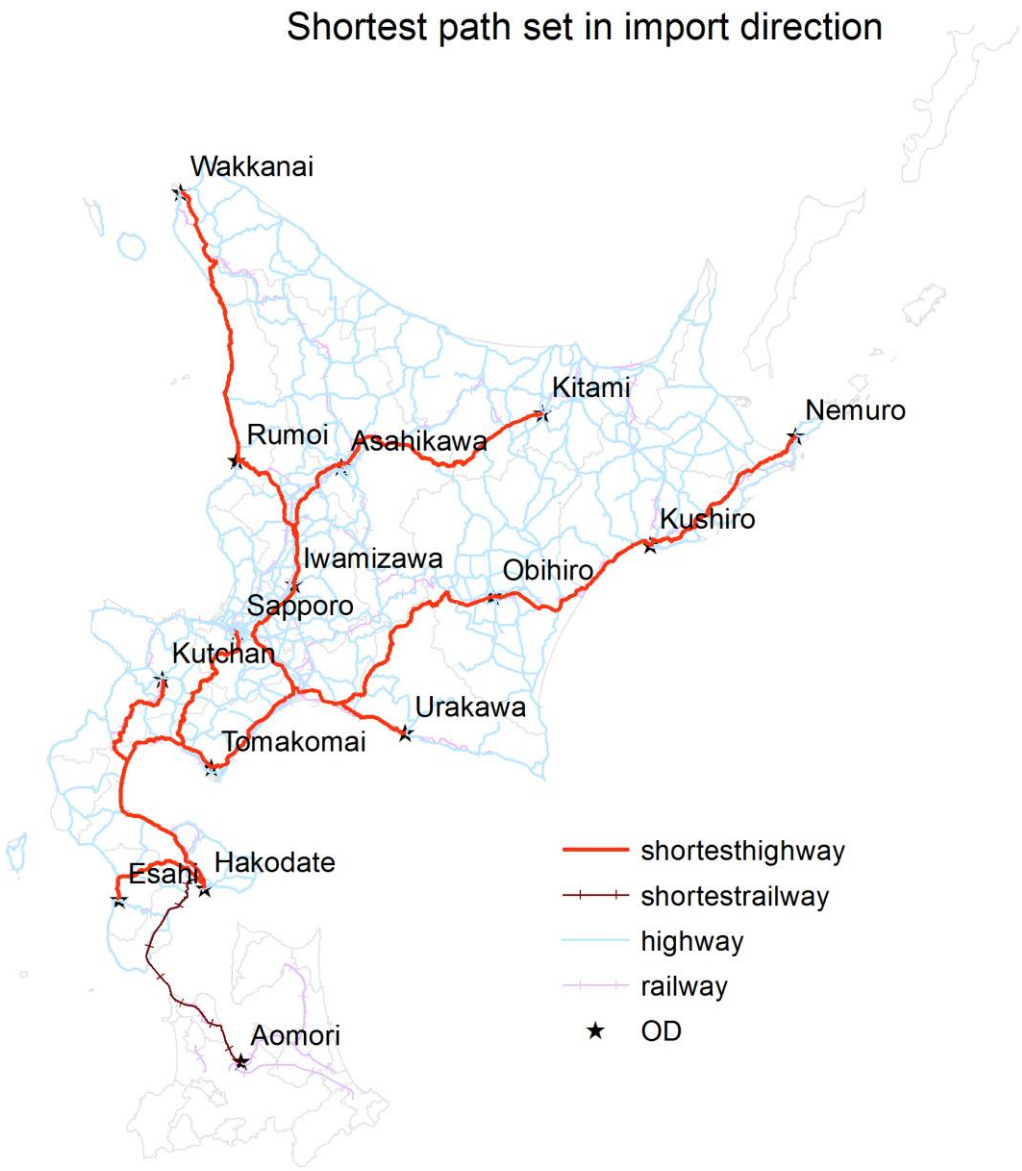

Figure 33 Shortest path set (import direction)

Figure 34 Shortest path set (export direction)

5.7.2 Results of vulnerability scanning

Furthermore, GIS techniques are used to build visual display of vulnerability scanning results, as shown in Figures 35 and 36. Figure 35 shows the results of vulnerability scanning under export demand volume and Figure 36 shows the results under import demand volume. These results show that vulnerability of transportation network is not only impacted by the topological structure of the

network, but also traffic volume in the network. Links are ranked by seismic vulnerability index and classified into 7 categories, shown as different colours in Figure 35 and Figure 36. These categories are classified according SVI rank. The relationships between these categories and SVI are shown in Table 5.

"Blacklink" is a category in which some od pairs cannot be connected when links are disrupted by seismic disaster. Links in this category are most vulnerable to seismic disaster because their disruptions will cause od pair disconnection, which would be a dangerous situation for the regions which are unable to have logistics communication with others. "1~15" is a category in which links are ranked from 1 to 15 according to the SVI. Links in this category have the highest SVI, which means they are very vulnerable under seismic disaster. Similarly, "15~40", "40~70", "70~100" and "100~200" are categories of links ranked in order of decreasing SVI. The higher SVI, the more vulnerable the link is. Vulnerable links can be easily identified in these maps. Links in category "200~" have very small SVI, meaning that they are least vulnerable to seismic disasters and may require fewest reinforcement resources.

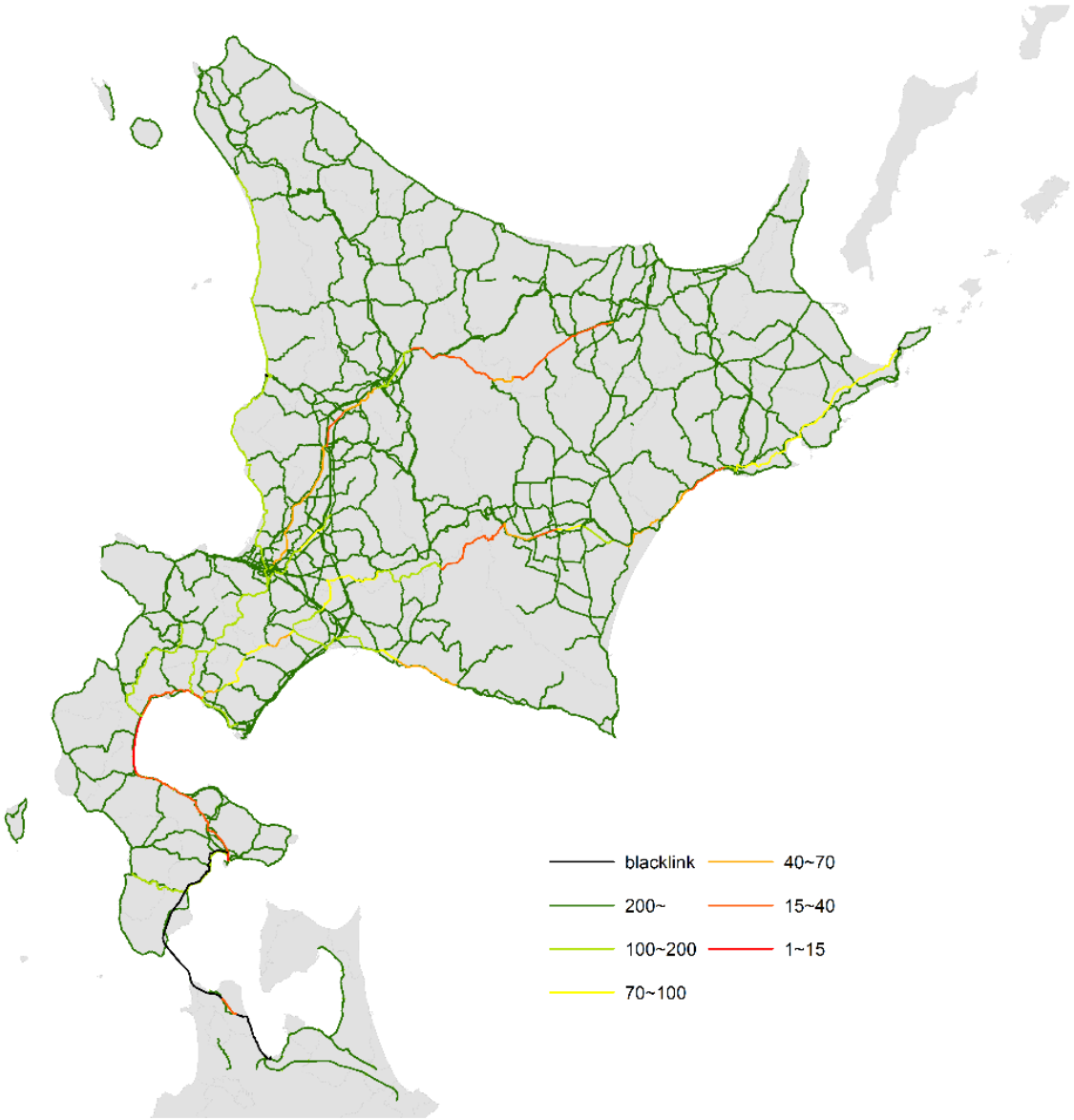

Figure 35 Link categories by seismic vulnerability index (export direction)

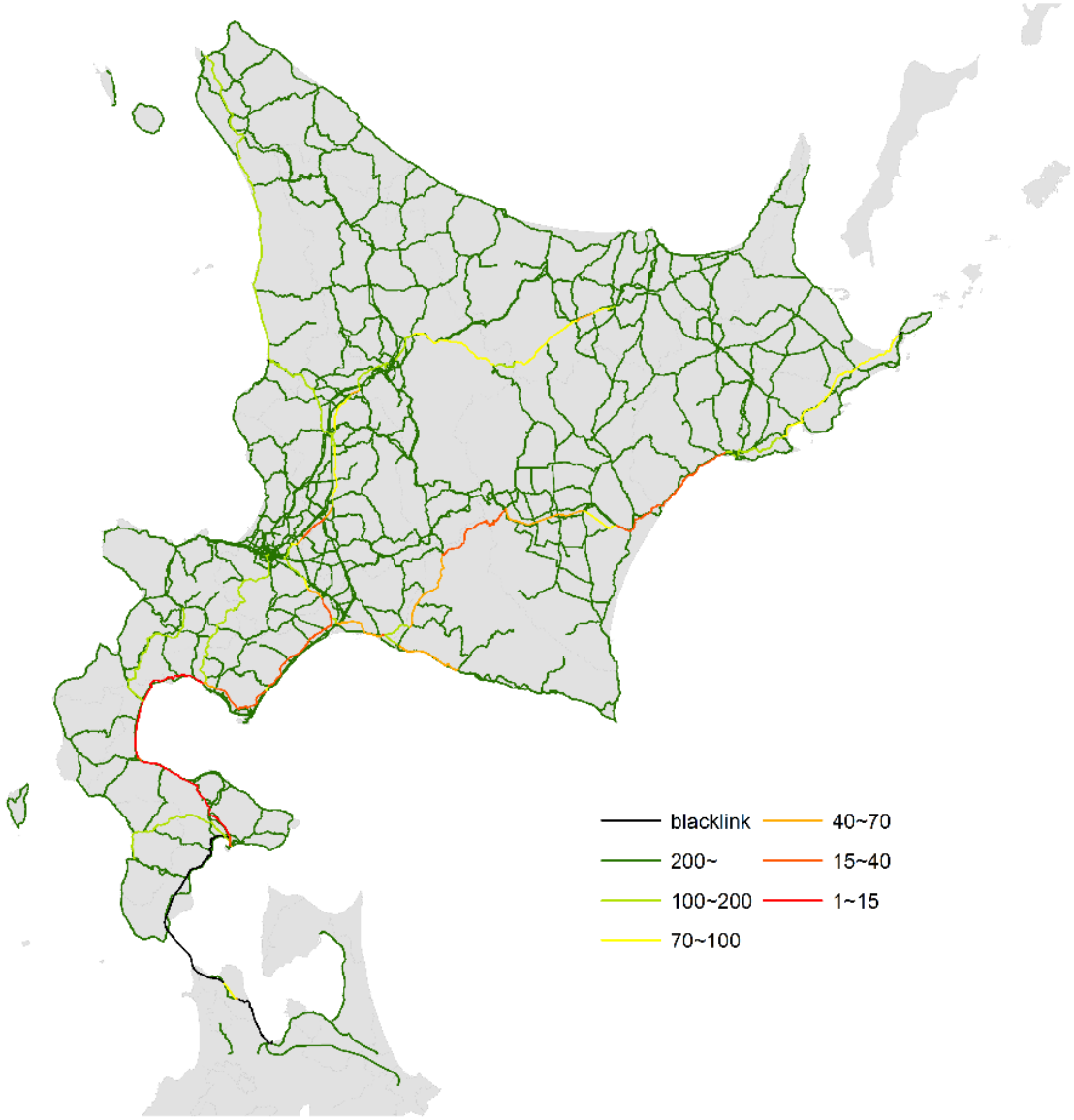

Figure 36 Link categories by seismic vulnerability index (import direction)

Comparing Figure 35 and Figure 36, the difference in vulnerability scanning results can be found between the "export" and "import" scenarios. In category "blacklink", links are exactly the same (according to detailed simulation results) in these two scenarios, meaning that their disruptions will cause some od pairs to be topologically disconnected, and this result is not related to traffic demands. These links are topologically vulnerable and have no alternative links for connecting od pairs. The links in this category are railway section from Hokodade freight station to Aomori freight terminal. This section consists of the Seiken tunnel that is the only railway connection between Hokkaido and Honshu across the Tsugaru Strait. This result reconciles with our intuitive judgement that the only

connection between two isolate area much be vulnerable port of transport network to disruption. Distributions of links in “1~15” category are different in the two scenarios, but they also have common parts that are vulnerable in both export and import directions. For example, the highway section between Asahikawa to Kitami is much higher vulnerable rank in export scenario that import scenario. This can be explained that Kitami has much agriculture to transport volume out of Hokkaido shown as Figure 27 and this highway section is much shorter than other routes. Additionally, this section also doesn’t have parallel and alternative routes. The section from Muroran to Hakodate has both different parts and common parts between the export and import scenarios. The different parts are near Muroran, which have much higher ranks in import scenarios than export, because there is a high transport volume in import but not export, as shown in Figure 27. The common part is near Hakodate, which shows that all logistics volumes from/to other areas of Hokkaido are through this section connecting to railway to Honshu. Distribution of links in the “15~40”, “40~100” and “100~200” categories are also different under these two demand scenarios. Distributions of links in the “200~” category are quite similar, meaning that these links are not so vulnerable in either scenario. Comparing “SVI range” of vulnerable categories in Table 5, SVI in export scenarios is much smaller than in import scenarios. However, the export logistics traffic volume is much bigger than import shown as Figure 27. This result shows that import logistics is more valuable and it should get more attention than export.

Additionally, to prove how degradation probability impact network vulnerability analysis, links are also classified by only consequence of network degradation without considering degradation probability. As described in methodology section, difference of total generalized cost (DTGC) is used to evaluate the consequence of link disruption, so links are also classified by DTGC to compare with the results of seismic vulnerability scanning. Links categories classified by DTGC are shown in Figure 37 and Figure 38. Figure 37 shows links categories classified in export direction, and Figure 38 shows this results in import direction. The relationships between these categories and DTGC are shown in Table 5. Comparing Figure 35 to Figure 37, links in “blacklink” category are exactly same, links in “1~15” category are similar but not exactly same which means the links in this vulnerable

level are different according to these two indices. Similar difference also can be found in other categories in these two figures and the obvious differences are marked by blue circles in Figure 37. Comparing Figure 36 to Figure 38, links in “blacklink” category are also exactly same, but obvious differences can be found in all other categories and some differences are marked by blue circles in Figure 38. From this result, we can conclude seismic vulnerability index is better to show network vulnerability under seismic disasters and its result is more meaningful to guide making seismic design of transportation facilities.

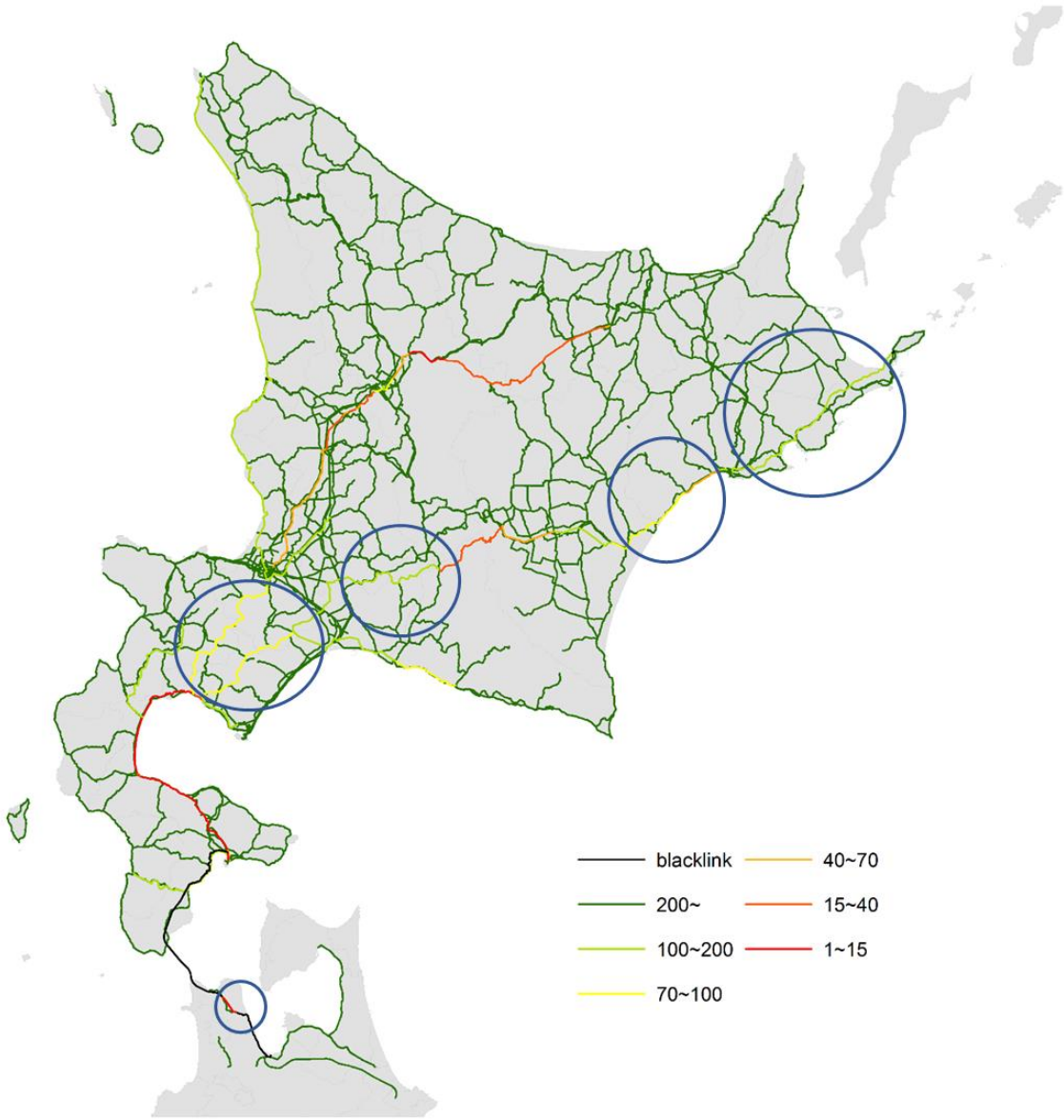

Figure 37 Link categories without considering probability of degradation (export direction)

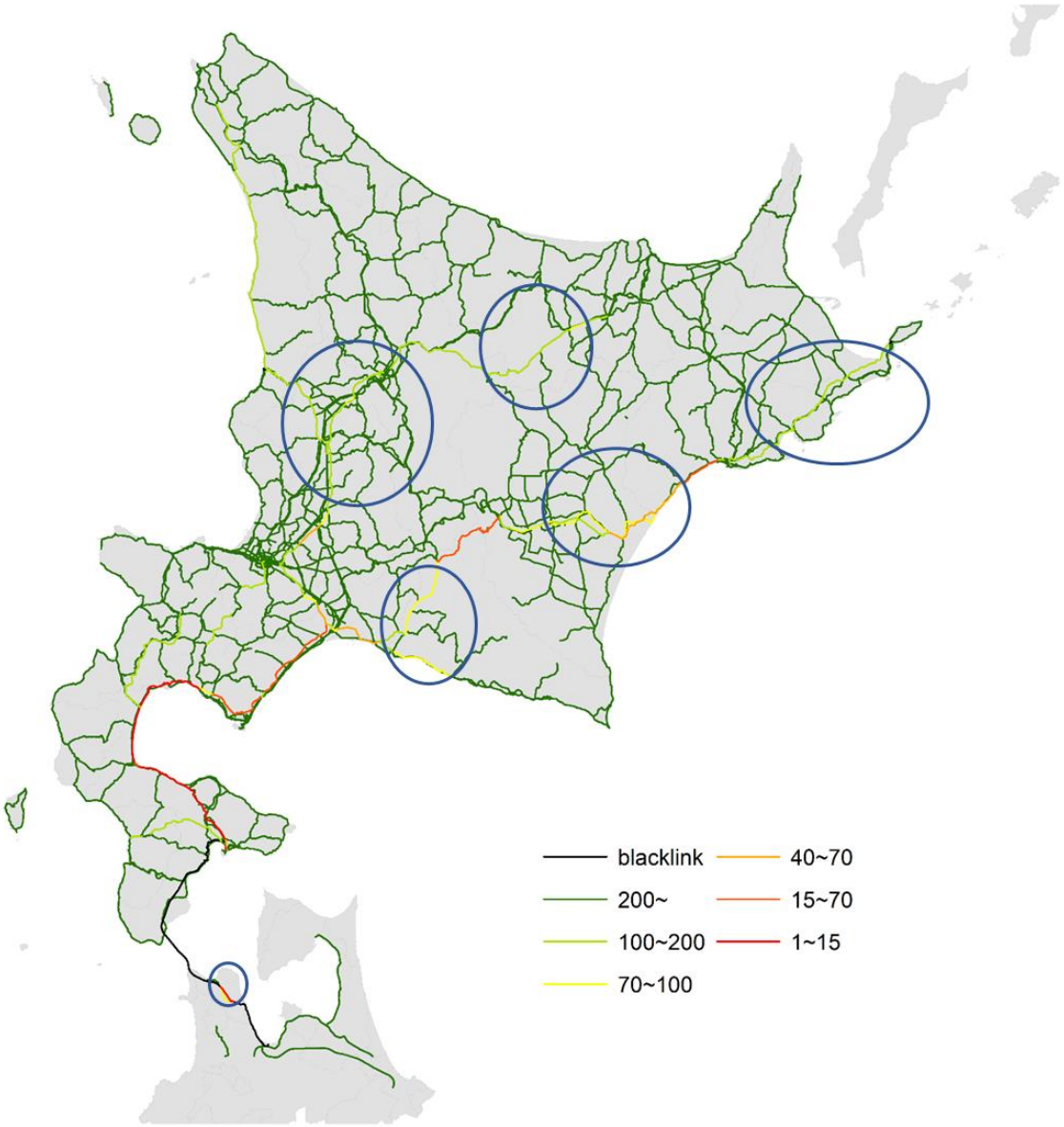

Figure 38 Link categories without considering probability of degradation (import direction)

Table 5 Vulnerable Categories and SVI, DTGC Values

Category name	SVI range (JPY/day)		DTGC range (JPY/day)	
	export	import	export	import
blacklink	-	-	-	-
1~15	73467.86~3183066	324779.1~5545561	117220~4854210	604562~8457040
15~40	11251.16~72896.07	63362.22~232042.1	24584~114139	86738~308868
40~70	4547.40~11014.74	27146.46~56817.04	9185~24059	54494~83588
70~100	2511.72~4135.30	12147.14~26887.32	4994~8459	30056~51680
100~200	20.13~2341.24	194.26~11884.61	51~4347	484~27668
200~	0~12.78	0~119.34	0~50	0~332

Note: SVI = seismic vulnerability index; DTGC = difference of total generalized cost; - = not available because some od pairs are not connected.

5.8 Conclusions

The Seismic Vulnerability Index is proposed to evaluate vulnerability of logistics transportation networks under seismic disasters, which considers not only the difference between the normal and degraded states of a network but also the probability of link disruption. Links of transportation network are ranked according to SVI and classified into different vulnerability categories. These results will assist in making reinforcement policies for transportation infrastructure to resist seismic disasters and improve the reliability of logistics transportation networks.

An efficient vulnerability scanning model is proposed to perform the application to complex transportation networks within reasonable time and computational demands. The methodology is applicable to sparse networks such as intercity logistics transportation networks, which are large scale but without congestion problems. Results of seismic vulnerability scanning are mapped using GIS techniques to visualize vulnerability distribution and make it easy to detect the vulnerable parts.

The methodology is applied to the logistics transportation network of Hokkaido. The results show that the most vulnerable parts in this network are in the railway section crossing Tsugaru Strait. The results also show that the vulnerability of links in a number of regions, particularly around the east coast of Hokkaido, is underestimated when the seismic probability is not considered. The seismic vulnerability assessment is a targeted analysis helping to realize concrete steps to mitigate the influence of seismic disasters.

According to link vulnerability categories, different measures can be taken to mitigate network vulnerability. For example, links in the “blacklink” category don’t have alternative routes in the logistics transport network. Measures like improving their structure strength to resist earthquakes or building alternative routes along them could be taken to mitigate their vulnerability. Links in higher vulnerable categories should have priority on seismic resistant reinforcement, or have more alternative links to mitigate network vulnerability. Additionally, possible modifications to a network could be modelled to assess potential improvements to reliability.

CHAPTER 6 CONCLUSIONS

6.1 Overall conclusions

Logistics generalized cost is proposed to describe the link impedance in logistics transport networks. It considers both the economy value of logistics industry and its transport value. Total generalized logistics transport cost reflects a global view in all users' benefit. It provides road network administrations assistance for benefit-cost-analysis. Diverse logistics traffic demands including volume and distribution diversity are applied in vulnerability scanning. The results show that traffic demands evidently influence vulnerability scanning results. The methodology proposed in this study is applicable to large scale and intercity logistics transport networks. Traffic congestion isn't considered when travel time is calculated, which is reasonable in intercity logistics transport network. The static shortest path model greatly improved calculation efficiency compared with others such as the user equilibrium model. Node vulnerability scanning methodology is also proposed besides single link vulnerability scanning. Links are usually used as the basic component of a network when network vulnerability is assessed, however this is not consistent with situations where area covering disasters occur and result in disruptions of more than a single link. In node vulnerability scanning, node failure supposes that all links connected to it fail, too. In the intercity logistics transportation system, this hypothesis can really explain the situation when disasters such as snow storms and floods happen to a transportation hub, causing all connected links to also fail. The results of node vulnerability scanning show us that the combination of links has a different character to its individual links, and it is necessary to do vulnerability scanning in various strategic levels. Even though node vulnerability scanning is new from link vulnerability, it is still closely related to link, and further discussion is needed to synthetically evaluate the vulnerability of individual links.

The Seismic Vulnerability Index is proposed to evaluate vulnerability of logistics transportation networks under seismic disasters, which considers not only the difference between the normal and degraded states of a network but also the probability of link disruption. Links of transportation network are ranked according to SVI and classified into different vulnerability

categories. These results will assist in making reinforcement policies for transportation infrastructure to resist seismic disasters and improve the reliability of logistics transportation networks.

An efficient vulnerability scanning model is proposed to perform the application to complex transportation networks within reasonable time and computational demands. The methodology is applicable to sparse networks such as intercity logistics transportation networks, which are large scale but without congestion problems. Results of seismic vulnerability scanning are mapped using GIS techniques to visualize vulnerability distribution and make it easy to detect the vulnerable parts.

The methodology is applied to the logistics transportation network of Hokkaido. The results show that the most vulnerable parts in this network are in the railway section crossing Tsugaru Strait. The results also show that the vulnerability of links in a number of regions, particularly around the east coast of Hokkaido, is underestimated when the seismic probability is not considered. The seismic vulnerability assessment is a targeted analysis helping to realize concrete steps to mitigate the influence of seismic disasters.

According to link vulnerability categories, different measures can be taken to mitigate network vulnerability. For example, links in the “blacklink” category don’t have alternative routes in the logistics transport network. Measures like improving their structure strength to resist earthquakes or building alternative routes along them could be taken to mitigate their vulnerability. Links in higher vulnerable categories should have priority on seismic resistant reinforcement, or have more alternative links to mitigate network vulnerability. Additionally, possible modifications to a network could be modelled to assess potential improvements to reliability.

6.2 Future work

This study proposed a scanning vulnerability methodology for logistics transportation networks. The methodology aims to be applied in practical networks. Several points in the study still need to be refined in future work.

- Integrated and international transportation is the tendency in modern logistics systems. Travel time and travel cost including transit systems, warehouse and other factors will be critical to building finer models describing logistics transportation features.
- Vulnerability of transportation networks can be assessed under any types of disruption if the probabilities of transportation facilities degradation data are available.
- The degradation patterns in vulnerability scanning can be extended to other modes such as administration boundaries, and geographic conditions according to the threat types or analysis aims.

6.3 Research contribution

Vulnerability assessment models for logistics transportation networks are developed in this study. Different from passenger transportation network, these models will provide a new point of view to apply vulnerability analysis into logistics transport networks and broaden the research fields of transportation network vulnerability.

Total generalized cost is proposed to evaluate the performance of logistics transport network which is measured by both travel time and travel cost. This measurement is more accurate to describe the character of logistics transport network.

Vulnerability scanning is conducted on multiple modes (link and node), evaluating network vulnerability under various degradation patterns.

Seismic vulnerability index is proposed to detect network vulnerable parts in seismic disaster attack. This tagged analysis is helpful to make vulnerability mitigation policy against specific disasters.

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