UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Civil, Maritime and Environmental Engineering and Science Unit

INTEGRATED VULNERABILITY ASSESSMENT OF TRANSPORT NETWORKS IN THE SEOUL CAPITAL AREA, KOREA

by

WONMAN OH

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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Although transport networks provide crucial infrastructure for mobility and accessibility in modern society, they are quite vulnerable to intended attacks, such as that in London in 2005, as well as natural disasters such as flooding and earthquakes. Consequently, it is important to assess the vulnerability of transport networks in order to increase their resilience and to provide travellers with a more reliable transport service. As all transport networks are highly interdependent and have a deep impact on each other's travel times, thus when assessing the vulnerability of transport networks, the relationships between different modes and total social travel costs should be considered.

This work assessed the integrated vulnerability of the whole transport networks in the Seoul Capital Area (SCA) of Korea, using the concept of total social travel costs (TSTC). TSTC was calculated by all travellers' travel time costs in the SCA as well as operating costs, road traffic accident costs, environmental impact costs, and parking costs, assuming a disruptive event on each section of the Seoul Metropolitan Railway Systems (SMRS). It was found that the 1st Incheon transport axis produced the biggest increase in TSTC, equivalent to a 3.8% increase compared with the TSTC of normal operation.

This work identified travellers' preferred choices when a disruptive event on the SMRS occurs, reflecting these choices in the revision of the normal origin/destination data, so that TSTC can be evaluated. An online survey of 1,415 respondents showed that 32% of travellers wanted to use the bus while 27% chose the car as their alternative transport mode for a disruptive situation on the SRMS.

This work suggests management strategies that can enhance the resilience of transport networks in the SCA. Using these management strategies, operators of the SMRS can respond efficiently to a disruptive event, while government can address the problem of relatively weak transport axes. In addition, travellers can recognise their potential alternatives when they cannot use their normal modes or primary routes. The management strategies were distilled from 19 interviews with experts from the operators of the SMRS, central and local governments of Korea, and professors or researchers in the field of transport networks.

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Declaration of Authorship

I, WONMAN OH,

declare that this thesis entitled

Integrated Vulnerability Assessment of Transport Networks in the Seoul Capital, Korea

and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. None of this work has been published before submission.

Signed:

Date: 11th June 2018

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List of Abbreviations

AHP	Analytical Hierarchy Process
APTB	Area Passenger Transport Business
AVTT	Average Value of Travel Time
BPR	Bureau of Public Roads of USA
BRIC	Brazil, Russia, India and China
BRT	Bus Rapid Transit
CBS	Cell Broadcasting Service
CIP	Critical Infrastructure Protection
CIPI	Critical Infrastructure Protection Information
CNI	Critical National Infrastructure
CPI	Consumer Price Index
EPCIP	European Programme for Critical Infrastructure Protection
ETA	Event Tree Analysis
EU	European Union
FKI	Federation of Korean Industries
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GDP	Gross Domestic Product
GIS	Geographic Information System
GRDP	Gross Regional Domestic Product
HRT	Heavy Rail Transit
KDI	Korea Development Institute
KOSDAQ	KOrea Securities Dealers Automated Quotation
KRW	Korean Won
LRT	Light Rail Transit
MER	Metropolitan Express Railway
MMA	Multi-modal Multi-class Assignment
MOE	Measure of Effectiveness
MOLIT	Ministry of Land, Infrastructure, and Transport
NIPP	National Infrastructure Protection Plan
O/D	Origin/Destination
OECD	Organization for Economic Cooperation and Development
PGS	Pain, Grief, and Suffering
PTN	Public Transport Networks
ROW	Right of Way
RPTB	Route Passenger Transport Business
SCA	Seoul Capital Area
SMRS	Seoul Metropolitan Railway Systems
SMS	Short Message Service
TSTC	Total Social Travel Cost
USD	United States Dollar
VDF	Volume Delay Function
VTT	Value of Travel Time
WTP	Willingness To Pay

Chapter 1 Introduction

1.1 Research Background

Chaucer, an English poet of the 14th C, said that all roads lead to Rome (1391). This phrase is one of the classic expressions showing the greatness of the Roman Empire's road infrastructure network. The Roman Empire survived for over 500 years with contiguous territories throughout Europe, North Africa, and the Middle East, because it had constructed and operated well-linked networks of roads, aqueducts, postal services, and so on. It is clear that well-developed infrastructure of the Roman Empire enhanced the efficiency of governance and communication between the Emperor in Rome and governors in local colonies. The importance of networks of infrastructure in the modern world is absolutely undeniable from the perspective of peoples' welfare and living standards (Jenelius and Mattsson, 2015). Companies' economic activities and governments' administrations are also highly dependent on the connectivity of diverse infrastructure. Networks of transport, electricity, telecommunication and waterways are basic foundations supporting the world, both locally and globally. Without widespread infrastructure networks, it seems that contemporary society would not continue even a day.

Among various networks of fundamental facilities, transport networks such as road, railway, and subway are crucial elements for both daily life and industrial activities: going to school, commuting to work, going shopping, delivering raw materials to industry, and delivering manufactured products from factories to customers. Transport networks are closely linked with demand when it comes to commuting and transport within a city's boundary or further into one-day life zones. Because of the complexity and connectivity of transport networks, they are sensitive to incidents that vary in scale and cause (Oh and Preston, 2017).

Berdica defined an *incident* as "an event, which directly or indirectly can result in considerable reductions or interruptions in the serviceability of a link/route/road network" (2002, p.118). Incidents on transport networks may include natural disasters such as floods, heavy snowfalls, earthquakes and volcanic eruptions. Terrorist attacks such as in New York in 2001, Madrid in 2004, London in 2005, and Brussels in 2016, are the other occasions where transport networks have been disrupted. Terrorist attacks have a low probability of occurring, but have high consequences. Another source of malfunction of transport networks may be related to maintenance and operation: mechanical faults, union strikes, accidents, and human error.

When there is a disruptive event on a specific section of transport networks, travelling by private car has more flexibility of re-routing and re-timing than using public transport, which is more likely to be affected by risks that cause reduced serviceability of public transport networks (PTN). Because of this, vulnerability studies in PTN are getting more important around the globe (Rodríguez-Núñez and García-Palomares, 2014). Although there are several competing characteristics between using private cars and using public transport, possible disturbances to the PTN may be one of the decisive factors that determine mode choice. In other words, a stable PTN service and good punctuality can be an incentive for people to choose a sustainable public transport system. Analyses of the weakness of PTNs are valuable to operators of transport networks to determine feasible alternatives in urgent situations. Additionally, central government can adjust the priority of infrastructure investment, by considering the vulnerability of a specific transport network.

Vulnerability assessment in PTN such as the Seoul Metropolitan Railway Systems (SMRS) cannot be identified clearly without considering adjacent road networks, which can provide supplementary functions with highly interlinked relationships. Of course, some travellers would cancel their original journeys or delay their initial trips because of the unavailability of a section of the SMRS. However, most travellers who cannot use a specific subway line probably continue their journey by taking a bus and a taxi or driving their own cars. They can also modify the normal route of the SMRS in order to escape the unavailable section, being partially supported by several transport modes of road networks. Therefore, it is important to identify the impact of a disruptive event not only on the SMRS but also on the adjacent road networks.

Vulnerability assessment in transport networks is an effective way to understand what would happen in the event of substantial malfunction of a specific transport network, and how to prepare an efficient solution in order to prevent a cascading result for the entire network. In the era of unpredictable climate and potential terrorism, transport networks, especially public transport modes, can be objects that may suffer substantial interruption. Indeed, the frequency of intended attacks on transport facilities has increased consistently. The scale of damage from natural disasters has also intensified. Considering these trends of disruptive events to transport networks, analysis of vulnerability is mandatory in order to provide for safer travel and a more reliable transport service.

1.2 Research Objective

This work first focuses on integrated vulnerability of transport networks and reflecting travellers' intended choice when transport networks are disrupted. The literature related to disastrous events expanded sharply as a part of the study in critical infrastructure protection since 9/11 (Jenelius and Mattsson, 2015). However, previous publications have not tried to relate different transport modes such as subway and road networks. Previous studies have also paid little attention to individuals' intentions for modes or routes in the event of disruption. Although Cairns *et al.* (2002) argued that there were probably diverse changes in travel patterns in the event of reduced transport capacity such as road closures, a definite relationship between disruption on transport networks and the loss of travellers was not identified. If it is assumed that most travellers have to continue their journeys notwithstanding troublesome environments, the impact on different modes and personal inclination to modes and routes should be reflected when assessing the vulnerability of transport networks.

The primary goal of this work is to assess the vulnerability of public transport networks using integrated analysis of the subway systems, the Seoul Metropolitan Railway Systems (SMRS), and road networks in the Seoul Capital Area (SCA), Korea. In contrast to previous research, an integrated vulnerability assessment of different transport modes will be identified in order to achieve original travellers' trip purposes. 'Integrated vulnerability' here means the assessment of vulnerability with a combination of subway systems and road networks. When an incident occurs on the subway networks, the influence on adjacent road networks, in addition to the impact on subway networks, will be taken into account in order to estimate the vulnerability of the entire transport network. This will be calculated by identifying the number of people transferring from the SMRS to road transport modes such as cars, taxi, scheduled buses, and emergency buses.

The second goal of this study is to determine the personal intentions for transport modes and routes in specific disruptive environments, during the process of vulnerability appraisal. When an abnormal situation occurs, personal attitudes are very different to those during normal circumstances, so that choices they make do not truly reflect individuals' inclination regarding mode choice and route selection. Since it is rare for travellers to experience an extreme incident, the data revealed does not properly explain travellers' choice in the situation. Therefore, stated intention is required so that the inclination of travellers can be analysed. Stated choice can be useful when it is difficult to acquire direct data because of low probability or a hypothetical situation. Little research has explored individuals' intentions in the field of security in public transport systems (Potoglou *et al.*, 2010). It would be useful to take personal factors into account when trying to understand mode choice in a disruptive situation.

An online survey was thus adopted to collect travellers' imaginary reactions to the disrupted operation of the SMRS.

The third goal of this study is to determine the weakest and the strongest transport axis among the six transport axes in the SCA, from the perspective of vulnerability to disrupting events. One of the traditional criteria for determining the priority of infrastructure investment is the feasibility analysis, based on economic benefits and costs. However, the current criteria of infrastructure investment cannot represent the vulnerability of transport networks, which may be different depending on the transport axis. Although the economic feasibility is mainly determined by the high demand for a specific facility, vulnerability of transport networks may be not significantly related to the population of the target region. Therefore, it is useful to identify the most vulnerable transport axis from a viewpoint different to the economic feasibility analysis. Since central or local governments have limited budgets, it is important to know the priority, so that they can be prepared for situations such as flooding, fire, intentional attacks, and so on. Moreover, operators of the existing railway systems can optimise the Emergency Plan according to the priority of vulnerability of their infrastructures. Additionally, if adequate data were available for the transport networks of London or New York, the weakest transport axis of London or New York could be identified similarly.

Lastly, this work would establish management strategies to increase the resilience of the transport networks in the SCA and suggest guidelines for users in a disorderly situation. The purpose of management strategies is to prevent disruptive events on the SMRS and minimise the impact when disruptions do occur. Management strategies will be based on interviews with 19 experts, as well as the analysis of vulnerability of each transport axis, and the intention survey of commuters. Given such management strategies, governments can bolster relatively weak areas so that the decreased serviceability of transport networks is minimised. Operators of the SMRS can enhance their ability to respond with well-prepared equipment and trained human resources. Furthermore, travellers can recognise their potential alternatives when they cannot use their normal modes or primary routes due to trouble.

1.3 Vulnerability of Transport Networks

1.3.1 Critical Infrastructure Protection

Vulnerability analysis of infrastructure, including transport networks, has almost the same history as critical infrastructure protection (CIP), around the beginning of the 21st century. In fact, it may be said that vulnerability analysis of socio-economic core facilities is a response from the academic sector to a highly risky world. In this vein, understanding the concept and background of CIP would be helpful for figuring out the context of vulnerability analysis. The main documents arose from the USA, EU, and the UK.

The first announcement of CIP was the American Presidential Decision Directive PDD-63, made by the USA in May 1998. This was updated in December 2003, through Homeland Security Presidential Directive HSPD-7 as *Critical Infrastructure Identification, Prioritization, and Protection*. According to the PDD-63, federal government organizations were chosen to develop and implement plans for protecting government-operated infrastructures and cooperation required between government and the private sector to develop a National Infrastructure Assurance by 2003. Although the Directive called for both physical protection and cyber safety against both man-made and natural events, the real implementation focused on cyber protection against man-made cyber events (i.e. computer hackers). After experiencing the destruction and disruptions caused by the 9/11 terrorist attacks in 2001, the nation sharply increased attention toward physical protection of critical infrastructures (Moteff, 2015).

In July 2002, the USA's National Strategy for Homeland Security defined Critical Infrastructure as those "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" (OFfice of Homeland Security, 2002, pp.29-30). Thirteen critical infrastructure sectors were identified: agriculture, food, water, public health, emergency services, government, defence and industrial base, information and telecommunications, energy, transportation, banking and finance, chemical industry and hazardous materials, postal and shipping (OFfice of Homeland Security, 2002).

In the USA's National Infrastructure Protection Plan (NIPP) 2013, national well-being was very dependent upon secure and resilient critical infrastructure that buttressed American society. To achieve this security and resilience, "critical infrastructure partners must collectively identify priorities, articulate clear goals, mitigate risk, measure progress, and adapt, based on feedback and the changing environment" (Homeland Security, 2013, p.1). Managing risks from significant threat and hazards to physical and cyber critical infrastructure required an integrated approach across this diverse community: owners and operators; Federal, State, local, tribal, and territorial governments; regional entities; non-profit organisations; and academia. The purpose was to identify, deter, detect, disrupt, and prepare for threats and hazards to the nation's critical infrastructure, to be achieved by five activities: prevention, protection, mitigation, response, and recovery. Cooperation and sharing of information between the public sector and private operators were strongly highlighted to tackle the risks (Homeland Security, 2013).

The European Programme for Critical Infrastructure Protection (EPCIP) indicated the principles and specific programmes created as a result of the European Commission's directive. The EU Commission (2004, p.3) defined critical infrastructure this way:

> "Critical infrastructures consist of those physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, will have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments in the member states. Critical infrastructures extend across many sectors of the economy, including banking and finance, transport and distribution, energy, utilities, health, food supply and communications, as well as key government services".

The EU Commission (2006, p.3) declared the key principles that would guide the implementation of European Programme for Critical Infrastructure Protection (EPCIP):

- Subsidiarity – The Commission's efforts in the CIP field would focus on infrastructure that is critical from a European, rather than a national or regional perspective.

- Complementarity – The Commission would avoid duplicating existing efforts whether at EU, national or regional level, where these have proven to be effective in protecting critical infrastructure. EPCIP would, therefore, complement and build on existing sectoral measures.

- Confidentiality – Critical Infrastructure Protection Information (CIPI) would be classified appropriately and access granted only on a need-to-know basis. Information sharing regarding CIPI would take place in an environment of trust and security.

- Stakeholder Cooperation – Including private owners/operators of critical infrastructure, relevant stakeholders would be involved in the development and implementation of EPCIP.

- Proportionality – Measures would only be proposed where a need has been identified following an analysis of existing security gaps and would be proportionate to the level of risk and type of threat involved.

- Sector-by-sector approach – Since various sectors possess particular experience, expertise, and requirements with CIP, EPCIP would be developed on a sector-by-sector basis and implemented following an agreed list of CIP sectors (EU Commission, 2006, p.3).

The UK's Cabinet Office (2010) defined the Critical National Infrastructure (CNI) as: "Those infrastructure assets (physical or electronic) that are vital to the continued delivery and integrity of the essential services upon which the UK relies, the loss or compromise of which will lead to severe economic or social consequences or to loss of life" (p.8). The National Infrastructure is categorised into nine sectors: energy, food, water, transportation, communications, emergency services, health care, financial services and government (Cabinet Office, 2010). National resources can be deployed as effectively as possible to protect the infrastructure that is deemed most critical, according to the prioritised list of assets (HM Treasury, 2014).

The aims of the Critical Infrastructure Resilience Programme are to:

> "reduce the most substantial risks to the continuity of critical infrastructure and essential services resulting from severe disruption caused by natural hazards; provide a shared framework to support cross-sector activity to assess, enhance and sustain the resilience of critical infrastructure and essential services to disruption from natural hazards; enhance the collective capacity of critical infrastructure to absorb shock and act quickly when faced with unexpected events; ensure an effective emergency response at the local level through improved information sharing and engagement before, during and after emergencies" (Cabinet Office, 2010, p.9).

1.3.2 Characteristics of Urban Transport Networks

Mobility of people and diverse goods can be achieved through transportation infrastructure network services. Without transport networks, there is little connection between people, products, and services (Faturechi and Miller-Hooks, 2014). Transport networks have spread nationwide and globally in order to connect all origins and destinations. However, transport networks have different characteristics according their locations and their environments. Urban transport networks in particular have several characteristics different from other infrastructure such as water delivery, telecommunication, or electricity supply. Traffic facilities are concentrated in urban areas. Traffic congestion usually happens in the morning and evening, which is mainly caused by commuting to work or returning home. Most cities also commonly provide convenient and economic public transport networks for their citizens and visitors. However, urban public transport networks can be vulnerable to disruptive events since they have pre-determined timetables, high volume/capacity ratio, and very complicated structures that provide a useful transfer service among diverse travelling modes.

The first characteristic of the urban area is that transport facilities are clustered there, compared with the rural area. This is to provide large numbers of travellers with convenient and efficient mobility methods. Highly dense road networks link all destinations within urban area by car, taxi, and intra-city bus. A Bus Rapid Transit (BRT) service may be operated in order to provide for relatively long-distance trips. Subway systems and general railways pass through major transport axes to supply travellers with high degrees of punctuality. Some cities operate trams as a major railway service. Thus, people in cities have many opportunities to use diverse transport modes without long waiting times.

The second characteristic of urban transport networks is traffic congestion. This occurs when traffic volume is greater than road capacity. Traffic congestion in the peak travelling hours occurs generally in specific areas at specific times. Traffic congestion is typically direction-related, varying with time of day. If one side of a road is highly congested in the morning, the other side would be crowded in the evening. The main reason for this phenomenon is commuting to work from home in the morning and *vice versa* in the evening. Of course, if the capacity of the road is not adequate, there may be continuous congestion all day. Spatial mismatch research tells us that traffic congestion is produced by a jobs/housing disparity (Cervero and Wu, 1997; Schwanen *et al.*, 2004). Since commuting to work is very inelastic on the condition of the transport networks, it is difficult to execute effective countermeasures. Different causes for traffic congestion are attributed to traffic incidents, road works and weather events. These occurrences have a tendency to decrease the current capacity of road networks and eventually cause congestion due to the mismatch between traffic demand and road capacity. Traffic congestion also causes vehicle exhaust gas air pollution, so that environmental impact costs are normally taken into account when assessing the economic feasibility of transport infrastructure investment projects.

The third focus is on public transport networks that contribute greatly to economic efficiency, and a realistic solution to limited land availability in urban areas. Public transport has a fixed route and a scheduled timetable. Its service is for many unspecified travellers. Modes of public transport are: bus, BRT (Bus Rapid Transit), LRT (Light Rail Transit), and HRT (Heavy Rail Transit). Buses are inexpensive to manufacture and its service route is quietly demand-responsive. However, the bus has poor punctuality because it is very sensitive to traffic congestion. BRT can overcome the poor punctuality of the normal bus when it is given the exclusive lane for rapid operation. Although heavy rail transit has the largest capacity, its construction and operating costs may be a substantial burden on the local authorities. LRT has intermediate characteristics between BRT and HRT with low noise and vibration, normally connecting satellite cities with mega cities or sightseeing towns (Vuchic, 2002).

The final characteristic is that urban transport networks are quite vulnerable to intentional attacks. Terrorists' attacks in Madrid in 2004 and in London in 2005 are representative cases that reveal the vulnerability of public transport systems. Since many unspecified travellers use bus or subway frequently, it is not easy to check their security in detail. Additionally, the operating schedule of public transport is basically pre-determined and announced for information and timekeeping, which can be a weak point for intentional attacks. Complex structures for connecting different modes or other lines may be a target that could generate an enormous impact. Natural events as well as intentional disruptions can damage a fixed route mode such as subway or railway. For instance, rails can be flooded or a subway station inundated by heavy rain. Subway stations that are underground are particularly susceptible to a flood arising from climate change. Human error that may occur during operation and maintenance also causes the malfunction of public transport and potential damage to travellers. Deviation or collision occasionally happens and causes substantial casualties and property loss.

1.3.3 Disruption and Vulnerability of Transport Networks

Using a wider prism of natural disasters, it was reported that OECD and BRIC countries had experienced an estimated USD 1.5 trillion in economic damage from disruptive shocks in the last 10 years. The disruptive events included natural risks like storms or floods, as well as man-made risks like industrial accidents or terrorist attacks. In the case of the recent earthquakes in New Zealand and Chile, even single shocks caused damage in excess of 10% of national GDP. However, major shocks are no longer confined to single places, but rather cascade regionally and globally. The Great East Japan Earthquake (2011) and the major floods in Thailand (2011) were typical instances for this cascading effect. To make matters worse, disruptive shocks seem to be occurring more frequently and have become more intense and complex. It is argued that urbanisation and increased global economic integration has reinforced and accelerated this dynamic impact, which is facilitated by transport mobility and communication acting as a vector for propagating shocks globally (OECD, 2013; OECD, 2014).

Table 1-1. OECD Human and Economic Losses across Disaster Types (1973-2012)

Type of Event	Ave. Economic Losses (USD 1,000)	Ave. People Affected	Ave. People Killed	Total No. of Events
Earthquake	2,571,453	63,836	338	210
Storm	659,870	28,190	17	1,138
Flood	261,554	34,150	13	711
Wildfire	208,949	6,318	5	183
Extreme Temperature	166,144	26,301	458	184
Industrial Accidents	136,681	3,250	16	261
Mass Movement Wet	36,544	1,580	26	86
Volcano	32,373	10,011	8	33
Miscellaneous	5,943	58	29	212
Transport Accidents	49	8	34	679
Epidemic	0	55,674	13	47
Mass Movement Dry	0	333	94	3

Source: EM-DAT: The OFDA/CRED International Disaster Database,
http://www.emdat.be/ (OECD (2013))
Ave. means average values per event

Mass media and academic groups have also illustrated damage from disruptive incidents. WABC-TV (2012) reported that Hurricane Sandy (2012) caused losses to the New York transportation system of approximately USD 7.5 billion. Hurricane Irene (2011) disrupted more than 500 miles of highway, 2,000 miles of roadway, 200 miles of railway, and 300 bridges in Vermont (Lunderville, 2011; Mears and McKearnan, 2012). The collapse of the I-35W Bridge over the Mississippi River (2007) caused daily passengers to re-route and eventually inflicted over USD 0.4 million in costs on them (Zhu *et al.*, 2010). Gordon *et al.* (2007) reported a 6% decrease in the number of trips and a large shift from public transport services to private cars during a two-year period following the 9/11 attacks.

The OECD defined a disruptive shock as:

> "a situation that causes serious damage to human welfare, the economy, the natural environment or (inter)national security, where serious damage is defined as: loss of human life; human illness or injury; damage to property or infrastructure; homelessness; business interruption; service interruption (including health, transport, water, energy, communication); disruption in the supply of money, food or fuel, contamination or destruction of the natural environment" (OECD, 2003, p.10).

Jenelius and Mattsson (2015) claimed that disruption could be caused by events within the transport system, including road traffic accidents and technical failures. On the other hand, external constraints could be imposed on the system, often caused by nature, as with floods, landslides, heavy snowfall, storms, wildfires, earthquakes, etc. In addition, intentional disruptions could also obstruct a fundamental function of transport networks and might trigger severe damage in terms of casualties.

After recognising the impact of disruptive events, it is necessary to understand the specific differences between various terms used in the disaster literature. Berdica (2002) conceptualised vulnerability-related terms, while Faturechi and Miller-Hooks (2014) illustrated a remarkable classification and explanation of these terminologies: risk, vulnerability, reliability, robustness, flexibility (also known as agility and adaptability), survivability, and resilience. Some core terminology such as incidents, risk, vulnerability, and reliability are summarised in Table 1-2.

Table 1-2. Overview of Core Terminologies in Infrastructure Disasters

Term	Definition
Incident	• Events that can directly or indirectly result in considerable reduction or interruption in the serviceability of a link/route/network. • Frequency, predictability, and geographical extent vary according to the category of event. • Extreme weather (flooding, heavy snow), earthquakes, volcanoes, physical failures, road traffic accidents, maintenance works, labour strikes, fire, explosions, intentional attacks.
Risk	• A combination of the probability of an event and its consequences in terms of system performance. • Risk is generally associated with something that entails negative consequences for life, health, and the environment.

Term	Definition
Vulnerability	• Susceptibility of the system to incidents that can result in considerable reduction in transport network serviceability. • Consequence minimisation is important since it is not feasible to talk about the probabilities of certain incidents, e.g. terrorist actions. In those cases, it is necessary to investigate expected effects and possible remedial actions assuming that the incident has already taken place.
Reliability	• The probability that a system remains operative at a satisfactory level post-disaster. • Used extensively where failures can be recurrent, and thus their probability of occurrence may be significant and predictable.
Robustness	• The ability to withstand or absorb disturbances and remain intact when exposed to disruption. • Robustness assesses the remaining functionality compared with Reliability that considers the probability of meeting a given level-of-service.
Resilience	• The capability of returning to normal operation after having been disturbed, or reaching a new state of equilibrium. • Resilience involves the maximum disturbance from which the system can recover, and the speed of recovery.

Source: Berdica (2002, pp.118-120); Faturechi and Miller-Hooks (2014, pp.2-3)

The previous section discussed the significance of responding actively to diverse disruptive events to keep the surroundings safer and minimise the damage. Now, the achievements and limits of current publications will be reviewed, showing the need for a different approach to identify the core vulnerability of public transport networks.

Rodríguez-Núñez and García-Palomares (2014) pointed out that for a long time most research had been carried out on road networks, although public transport networks were more sensitive to vulnerability (See examples: Berdica (2002); Jenelius *et al.* (2006); Taylor *et al.* (2006); Berdica and Mattsson (2007); Jenelius (2009); Jenelius (2010); Chen *et al.* (2012); Jenelius and Mattsson (2012); Taylor and Susilawati (2012)). The most common indicator used was accessibility, when the vulnerability of road networks was assessed from a geographical perspective or for transport planning purpose. Even when public transport networks were covered, the major methods applied were graph theory indicators within the context of more recent complex network theory. However, these metrics were not a new approach. Garrison (1960) and Ratliff *et al.* (1975) had already used them to measure the increase in topological distance resulting from disruption in certain links and to identify the most critical links of a network.

Recently, the development of more competent computer applications has stimulated a considerable expansion in this type of study. For example, Derrible and Kennedy (2010) studied the form and structure of different subway networks, analysing 33 of them. Bono and Gutiérrez (2011) incorporated network theory indicators to assess vulnerability and used GIS tools for visualising and analysing results. Some recent studies have tried to combine complementary information into graph theory indicators. However, as Matisziw *et al.* (2009) pointed out, most literature still adhered to the network structure analysis. Therefore, it is necessary to take into account data on trips distribution, network capacity, and the cost of travel, for a more comprehensive analysis on the operation of public transport systems.

The majority of current publications focused on the structural analysis from the approach of graph theory, that omitted consideration of the travellers' viewpoint. Previous research also lacked integrated approaches that could handle different transport modes in an urban area. When a disruptive event happens in a part of the subway network, travellers have a tendency to find an alternative within the subway network or to shift to another mode, since they want to complete their original trip purposes notwithstanding increased costs or risks. In particular, commuters may be inelastic to disturbing incidents and they want to finish their journeys another way, since commuters' trips are highly related to their economic outcomes. Consequently, when a disruptive incident occurs in one transport mode, for instance, subway networks, the adjacent road networks receive a derived influence as well. These modes must be associated in order to assess the integrated vulnerability across the entire transport networks.

Since it is clear that people's responses to the abnormal situations are different, it is more reasonable to take into account personal intentions regarding choice of transport modes in specific disruptive environments. There have been few studies that have considered personal intentions when assessing the vulnerability of specific transport networks. Therefore, it is important that individual choice is dealt with in relation to degradation of a particular mode of transport, to establish enhanced assessment of the vulnerability of transport networks in a highly developed urban area.

1.4 Scope of the Thesis

The objective of this work is to identify the vulnerability of transport networks using an integrated approach between modes from the individual users' perspective, in the Seoul Capital Area. Specifically, the primary goal of this study will be analysis of the vulnerability of each transport axis around Seoul in terms of total social travel costs (TSTC). Regarding vulnerability of the transport networks, trip purpose, and reliability of travel time, a wide range of focus has been found in the relevant literature. Therefore, the limits of this study need to be clarified first.

In general, four approaches for the assessment of vulnerability of transport networks have been tried: the scenario-specific approach, the strategy-specific approach, the simulation-based approach, and mathematical modelling assessment. In this work, the scenario-specific approach will be adopted by assuming that a specific section of each subway line in the SCA will become unavailable due to a disruptive event for one day. The suspended section of the SMRS will be from the starting station to the last station at the boundary of Seoul Metropolitan City and its neighbouring satellite cities according to each transport axis. Given the assumption of the suspended SMRS, travellers should make a detour by other subway lines, bus, taxi, or car. There are six transportation axes around Seoul: Incheon, Suwon, Seongnam, Namyangju, Uijeongbu, and Goyang. The vulnerability of all six transport axes will be analysed to compare their relative weakness.

Next, there will be a focus on the trip for commuting to/from work, when this research will recruit participants for an online survey to identify travellers' preferred choices during disruptive events on the transport networks. The main reason for this is that commuters are relatively inelastic to the disruptive situation on the transport network, in addition to using the opportunity to collect data for each of the six transport axes[1]. In general, commuting to or from work is uniquely compulsive and inevitable compared to other trips: shopping, leisure, social activities, and personal business. Although commuting to or from school is also compulsory, the number of trips by car or public transport is smaller than commuting to work since a large number of school trips involve walking, given the principle of local school catchment . Commuting trips also have space-concentrating and time-concentrating characteristics, which cause severe traffic congestion on a particular transport axis or route in the morning or evening. In the SCA, residential suburbanisation has made the distance of the commute much longer than in the past, which

[1] According to 2014 Revision of Origin/Destination Data in the SCA, there were 58,773,185 trips per weekday. Returning home amounted to 25,016,108 trips per weekday, 42.6% of the total. The most frequent purpose for outbound trips from home was going to work with 11,289,241 trips, 19.2% of the total.

has deteriorated due to skyrocketing house prices[2] in Seoul in recent years. Commuters who live in the satellite cities pay a high travel cost, while they have few choices for jobs that are Seoul-based even though they experience much disutility. Thus, commuters' reaction to the problem of their main commuting routes would be useful when uncovering the vulnerability of transport networks in the SCA. Additionally, commuters' intentions will be generalised to calculate the total social travel costs (TSTC).

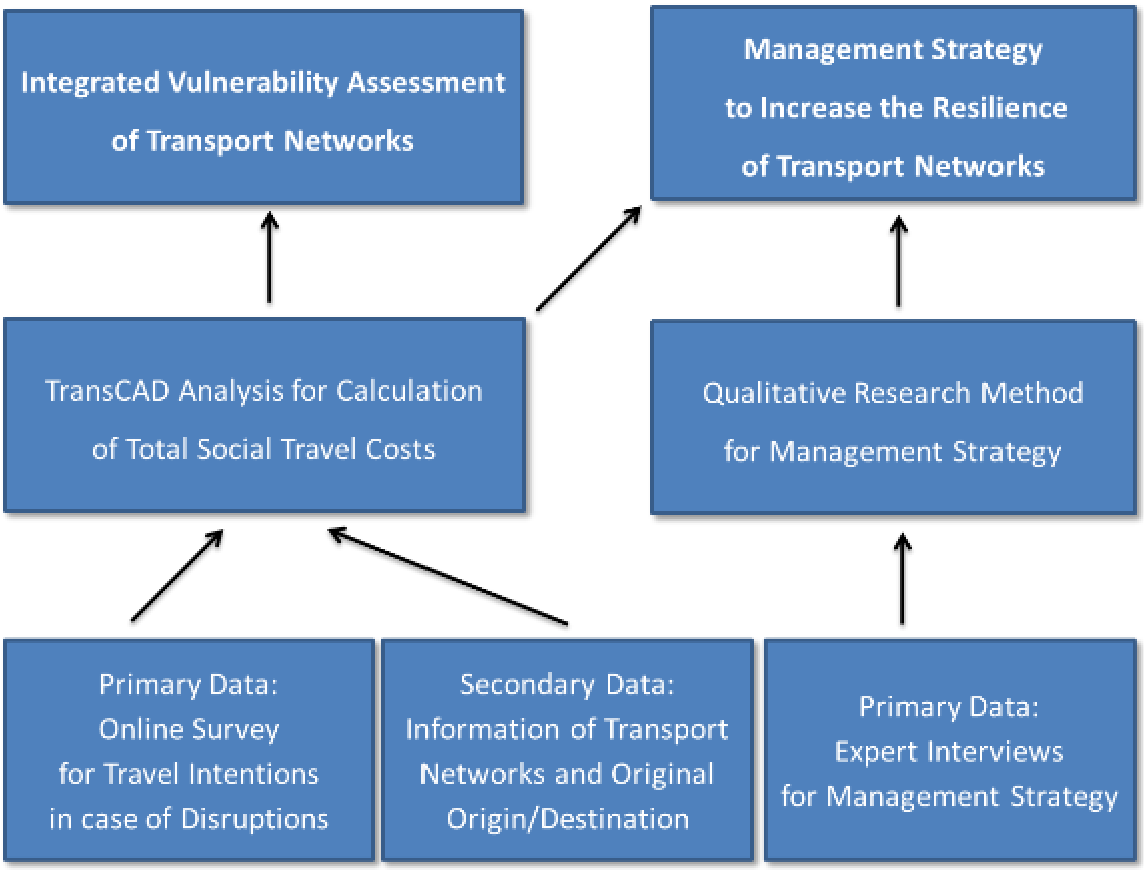
Lastly, among various functional indices to be used, travel time costs will be mainly chosen to compare the normal situation with a disruptive circumstance. Of course, operating costs of travellers, road traffic accidents costs, and environmental impact costs, will be also taken into account to secure a more realistic analysis. Faturechi and Miller-Hooks (2014) suggest that travel time is the most used performance indicator in vulnerability analysis. The travel time is especially compelling for commuters since there is usually a predetermined time to start work. Sikka and Hanley (2013) pointed out that commuters are sensitive toward travel time and determines travellers' route choice. To find the weakest transport axis, the integrated vulnerability of each transport axis will be calculated by the increased total social travel costs, by comparing the normal situation with the disruptive status. Travel time consists of usual travel time expected or predictable, and additional travel time linked to any unexpected or unplanned events, such as inclement weather, unanticipated traffic jams, or other disruptions. These unexpected delays are principal elements determining the travel time reliability, rather than the normal travel time that includes predictable delays (Sikka and Hanley, 2013).

[2] According to the Korea Appraisal Board, the average housing price index in Seoul in November 2003 was 68.4 while the average housing price index in May 2016 was 102.7, using June 2015 as 100.0. See http://www.r-one.co.kr/rone/resis/statistics/statisticsViewer.do?menuId=HOUSE_21111).

1.5 Overview

This work's data sources are two primary: the online survey for travel intentions in case of disruption with 1,415 participants, and 19 interviews with experts for management strategy; and one secondary data source: information on transport networks and original origin/destination in the SCA (Seoul Metropolitan Transportation Association, 2015). The online survey and transport networks information allow total social travel costs (TSTC) to be identified as the index of integrated vulnerability of transport networks. Additionally, qualitative research methods, applied to the expert interviews and TSTC calculation, will suggest management strategies for increasing the resilience of transport networks (Figure 1-1).

Figure 1-1. Overview of Methodology



Chapter 2 Literature Review

2.1 Overview

Research for measuring the performance of transportation infrastructure systems in disasters sharply expanded, both in depth and breadth, following development of post-disaster transportation systems after the 1995 Kobe earthquake (Chang, 2000; Chang and Nojima, 2001). Publications addressed much interest to terrorist attacks, such as 9/11 and bombings in Madrid (2004), London (2005), and Mumbai (2006), but also to natural disasters, such as Hurricane Katrina (2005), the Sichuan Earthquake (2008), the Christchurch earthquake (2011), and the Japanese Tsunami and subsequent nuclear meltdown (2011), (Faturechi and Miller-Hooks, 2014).

Faturechi and Miller-Hooks (2014) reviewed some 200 journal articles, conference proceedings, and technical reports that focused on the function of transport facilities in disruptive surroundings. They produced a well-organised categorisation using criteria: qualitative approach or quantitative approach, life-cycle phases of disasters, measures of effectiveness (MOEs), uncertainty modelling technique, and methodology. Qualitative approaches conceptualised important terminologies: risk, vulnerability, reliability, robustness, survivability, flexibility, and resilience. Quantitative analyses identified how to assess the performance of transportation systems by modelling or other types of decision support tool. When it comes to life-cycle phases of disasters, mitigation and preparedness were regarded as pre-disaster measures. Response and recovery were classified as post-disaster phases.

For MOEs, functional, topological, and economic measures were adopted as major frameworks. Functional measures mainly covered travel time, travel distance, traffic flow or throughput, and accessibility. Topological measures, based on graph theory, dealt with connectivity, spatial proximity, and centrality that covered the relative location of links and nodes in the network. Topological measures were primarily chosen by geography researchers to identify the weakness of transport networks. To define uncertainty of disruptive events, methods of scenario, simulation, probability distribution, and worst-case performance were suggested. Several articles studied a single historical disaster. Analytical methods, simulation, or optimisation models were identified for mathematical models of transport system performance. Analytical methods were applied through risk matrix, event tree analysis (ETA), fault tree analysis (FTA), failure mode and effect analysis (FMEA), and analytical hierarchy process (AHP). Monte Carlo simulation was frequently used to generate a large sample of scenarios.

The Faturechi and Miller-Hooks (2014) review clearly illustrated what had been done and how it had been done, in the area of the vulnerability of transport networks. From that review, this study will adopt the scenario method for a specific disruption on the SMRS and travel time cost as a MOE. Their research also suggested the need for ideas to increase the resilience of the transport networks.

Murray *et al.* (2008) classified network vulnerability analysis as scenario-specific, strategy-specific, simulation, and mathematical methodologies, and created an overview which clarified their advantages and limitations for both infrastructure planning and policy development. Scenario-specific approaches assess the potential consequences of an explicit disruption scenario such as the malfunction of an electrical substation or the collapse of bridge. This approach can produce relatively good analysis since it concentrates on the precise occasion. On the other hand, planning based on analysis of a single or a small subset of scenarios may overlook threats brought about by superficially unrelated (and unevaluated) scenarios. Consequently, "a focus on a single component or portion of an infrastructure of local interest can produce misleading insights on vulnerability at larger scales" (Murray *et al.*, 2008, pp.580-581).

Strategy-specific approaches tackle this kind of question: how vulnerable is a network to a structured or coordinated loss of facilities? The procedure follows a hypothesised sequence or strategy of disruption. Attackers would try to coordinate their attacks in terms of perceived facility importance order. Murray *et al.* (2008) claimed that this approach was effective for understanding the vulnerability of different situations to organised attackers' strategies.

Simulation-based approaches focus on the comparison of disruptive scenarios and their potential to impact infrastructure operation. To simulate a partial disruption to network facilities, many parameters are needed. Performance metric, probability information, and temporal and spatial scale characteristics, are essential for realistic simulation. Simulation can also be used to explore the dynamic vulnerability of transport network in relation to changes of disruptive events.

Simulation approaches are particularly helpful for demonstrating the scope of possible scenarios. Murray *et al.* (2008) pointed out a remarkable advantage of the simulation approach of prioritising scenarios in terms of management and disruption mitigation decisions. Mathematical modelling approaches pay attention to the most influential scenario that afflicts the network operation. Through mathematical modelling, the boundary of infrastructure networks can be identified, which is an inevitable element for all worst-case scenarios.

After comparing these four major approaches to assessing network vulnerability, Murray *et al.* (2008) emphasised the need for combining methods, since there are many perspectives on what aspects and conditions constitute vulnerabilities in assessing transport networks. Another reason for collaborative analysis is the dynamic characteristics of network vulnerability. Complementary functions of each approach would be useful to supplement or replace one for handling the switching nature of the problem.

The necessity of a combined approach, integrating each transport mode, is inevitable in developing a more realistic analysis in the event of disruption on the SMRS. It is also obvious that data on travellers' intended choices is necessary to accurately analyse the disrupted SMRS and impacted road networks.

2.2 Topological Analysis Approach

Murray (2013) addressed topological structure in a clear overview of network vulnerability modelling approaches. He defined and elaborated maximal flow, shortest path, connectivity, system flow, access fortification, and component attributes, to understand the graph theoretic characteristics of infrastructure networks. The maximal flow problem was to "find a network component set (nodes, arcs or combination of nodes and arcs) in the network that would minimise the maximum flow possible between an origin and destination pair of nodes if they were removed or rendered inoperable" (Murray, 2013, pp.211-212).

The shortest path meant not only physical distance but also travel time or cost. Access fortification is about important facilities for societal or national security, for example hospitals, emergency supply warehouses, fire stations, fuel supply depots. He also suggested future research areas related to vulnerability analysis: optimisation approach to identify worst case scenarios; game theoretic solutions for coordinated interdiction by terrorist attack; and application of geographic information system (GIS) and computing capabilities for enhanced detail and specificity in network vulnerability assessment.

As he suggested, this work will adopt the concept of worst case scenarios that were identified by comparing the *integrated* vulnerability of each transport axis within the six transport axes in the SCA.

Kim (2009) explored the network degradation's impact on the system flows and reliability of subway network systems in Seoul. The main questions in the area of network vulnerability were summarised as follows: "(1) what would be the outcome of a network in the face of unexpected disruptions?; and (2) what measures are effective to uncover network vulnerabilities for given networks considering its characteristics? " (Kim, 2009, p.189).

The research categorised previous literature as: strategy-based approach; simulation-based approach; and design-based approach. For example, the strategy-based approach mainly dealt with structural resiliency, network tolerance, and strategy to protect networks. The major methodologies for strategy-based approach were graph theory, statistical physics, and probability theory. The main focuses and methodology for each approach are given in Table 2-1.

Table 2-1. Approaches in Vulnerability Studies of Critical Infrastructure

	Focuses	Methodology
Strategy-based approach	Structural resiliency Network tolerance Strategy to protect networks	Graph theory Statistical physics Probability theory
Simulation-based approach	Plausible scenarios Network resiliency Preparedness in planning	Deterministic measures: connectivity, accessibility Graph theory-based index Probabilistic graph theory: survivability/reliability
Design-based approach	Less-disruptive network structure Back-up network design and facility location	Spatial optimisation techniques Probabilistic graph theory Mathematical programming

Source: adapted from Kim (2009, p.190)

In transportation systems, network reliability is defined as the probability of successful delivery of origin/destination flows without delay or loss in the network (Bell and Iida, 1997). O'Kelly *et al.* (2006) defined the reliability as "summing up the probabilities of all disjoint events for the successful connection between origin and destination nodes" (p.328). Mathematically, the computation of network reliability R_{ij} for origin i and destination j pair is as follows (O'Kelly *et al.*, 2006, p.328).

$$R_{ij}(G,P) = \sum_{k=1}^{n} P(D_k), \quad P(D_k) = \prod_{j=1}^{m} P(e_{kj}) \tag{2-1}$$

where

$R_{ij}(G, P)$: the reliability for two selected nodes, origin i and destination j,

G : a graph of network with given probability P for edges,

$P(D_k)$: the probability of the disjoint event D_k (k = 1 - n), and

e_{kj} : the edges j constituting D_k.

The probability of each D_k is calculated using Boolean algebra, which is the rule of complement set theory. Since all paths D_k are independent of each other, it is possible to assess the probability of deliverability of flows for OD pair throughout all enumerated paths simultaneously through summing up disjoint events probabilities $P(D_k)$ (Kim, 2009).

With the same computational method, the average network reliability AVR_{sys} from origin *i* to all the other destinations *j* can be extended as below (Kim, 2009, p.192).

$$AVR_{i,sys} = \frac{1}{{}_nC_2} \sum_{\substack{j=1 \\ (i \neq j)}}^{n} R_{ij} \tag{2-2}$$

where

$AVR_{i,sys}$: the average reliability from *i* to all other destinations *j* ($i \neq j$) on the network *G*, and

${}_nC_2$: the total number of *i-j* pairs

Only the topological structure is taken into account for the assessment of original reliability. If the amount of flow to be delivered for *i-j* pair W_{ij} is added to the equation (2-2), then the total amount of flows among the ODs would be calculated, as below (Kim and O'Kelly, 2009, p.289).

$$TFLOW_{i,sys} = \frac{1}{{}_nC_2} \sum_{\substack{j=1 \\ (i \neq j)}}^{n} W_{ij} R_{ij} \tag{2-3}$$

where

$TFLOW_{i,sys}$: the total amount of O-D flows to be delivered among *i-j* pairs on the network *G*

W_{ij} : the amount of flows to be delivered for *i-j* pair.

Table 2-2 illustrates the top/bottom ranking of 15 transfer stations by the reliability criteria among 55 transfer stations in the SMRS, Kim (2009).

Table 2-2. Top/Bottom 15 Transfer Stations by Reliability Ranking

The Top 15 Transfer Stations by Reliability Ranking					The Bottom 15 Transfer Stations by Reliability Ranking				
Rank	Transfer Station	AVR	TFLOW		Rank	Transfer Station	AVR	TFLOW	
1	Jongro3-ga	0.990928	231,832	(3)	41	Yeouido	0.981916	57,845	(25)
2	Euljiro4-ga	0.990920	32,048	(34)	42	Kkachisan	0.981728	53,282	(28)
3	Chungjeongro	0.990891	29,933	(35)	43	Eungam	0.981369	26,394	(41)
4	Seokgye	0.990887	29,456	(36)	44	Guro	0.981328	69,847	(22)
5	City Hall	0.990881	82,946	(18)	45	Cheonho	0.981315	77,971	(19)
6	Dongdaemun	0.990810	76,561	(21)	46	Bulgwang	0.981131	19,512	(49)
7	Euljiro3-ga	0.990805	88,141	(17)	47	Gasan Digital Complex	0.981092	46,084	(30)
8	Dongdaemun Stadium	0.990801	286,215	(2)	48	Dobongsan	0.980082	18,359	(50)
9	Sindang	0.990793	52,787	(29)	49	Yeonsinnae	0.972835	27,641	(40)
10	Dongmyo	0.990768	55,588	(26)	50	Suseo	0.972630	27,873	(38)
11	Sindorim	0.990756	320,165	(1)	51	Onsu	0.972417	13,770	(53)
12	Wangsimni	0.990752	99,565	(13)	52	Bokjeong	0.972222	9,598	(54)
13	Hapjeong	0.990730	103,799	(12)	53	Geumjeong	0.894339	21,885	(45)
14	Cheonggu	0.990712	15,185	(52)	54	Kimpo Airport	0.889666	19,686	(48)
15	Chungmuro	0.990687	166,500	(6)	55	Gangdong	0.888137	28,040	(37)

Source: Kim (2009, p.197)

Kim (2009)'s research was meaningful in identifying the SMRS from the standpoint of topological relations and determined a list of reliability for each stations. However, that research only dealt with the SMRS, and did not consider derived impacts on the adjacent road networks. The outcomes from Kim (2009)'s research gave a boost to an advanced approach for the integrated vulnerability between the SMRS and road networks.

2.3 Transport Function Analysis Approach

Jenelius and Mattsson (2015) described a process for large-scale road networks vulnerability analysis. Their conceptual framework was followed by the implementation of practical vulnerability indicators, computational methods, and algorithms. They suggested that vulnerability analysis should take into consideration different users under diverse scenarios, since there were various aspects of disturbances in transport networks. Therefore, a micro-economic approach was recommended and the individual user of transportation systems was viewed as a consumer of services and travel. From this viewpoint, "an increase in travel time meant that an individual might lose income, might have to sacrifice time from other activities, and might get reduced accessibility to societal services" (Jenelius and Mattsson, 2015, p.137). To assess the impact of a specific disruption scenario for a transport system user, the concept of *exposure to the scenario* was adopted. The exposure concept made it possible to compare the situations of different users who had various socio-economic, demographic and geographic backgrounds. Finally, Dijkstra's algorithm and a re-optimisation algorithm were applied to calculate the short path in the Swedish road transport network.

While the methodology of Jenelius and Mattsson (2015) suggested useful ideas about how the individual traveller was affected by partially closed road networks, it did not take into account transfer between transport modes. There was a need for investigation of travellers' intentions regarding alternative transport modes choice in the situation of disruptive events.

Cats and Jenelius (2014) introduced a dynamic and stochastic concept using mitigation effects of real-time information. From the perspective of supply dynamics, travel costs were determined by time-dependent alternative paths that had an impact on travellers' decisions. In other words, the spatial distribution of network vulnerability might also vary over time because the capacity or reliability of the transport networks was variable. They argued that transport service disruption would increase because of the dynamic nature of public transport supply, as well as reactions of travel demand to changes in supply. They tried to model a passenger's decisions through a probabilistic path choice, which was achieved by the traveller's access to real-time information on transportation system conditions. In order to reflect the interactions between public transport operations and traveller decisions, several variables were considered, such as vehicle capacities, dwell times, vehicle schedules, service disruptions, timetables, transfers, and walking distances.

This research by Cats and Jenelius (2014) suggested a perspective on how to deal with provision of real-time information for reducing disruption impacts. If travellers had correct information of disruptions on the SMRS, they could choose their optimal alternatives not spending unnecessary time travelling to the suspended section of the SMRS. This work thus also considered the problem of delivering information about the disruptive situation.

Rodríguez-Núñez and García-Palomares (2014) measured criticality and vulnerability in the subway network of Madrid through analysis of the consequences of a disruption in each link of the network. They measured the impacts on boarding times or the unsatisfied travel demand, which are typical indicators of serviceability in transport networks. Instead of using graph theory, they focused on lengthened riding times by analysing the actual network flow distribution of the Madrid Metro. The authors applied a full network scan method to analyse the impacts of disruption in each link of the network. One of their important findings is that the most critical link was in the area with a large number of trips but supported by a lower density of transport networks, which might result in long detours or abandoning the original trip. In addition, they found that the most critical links and the most vulnerable stations on the Madrid Metro network were located in the poorest sector of the city, which implied a relationship between transport networks vulnerability and social vulnerability. Although there are multimodal public transport networks in Madrid, the research only covered the Metro network to assess its vulnerability. This research was also limited by not addressing inelastic demand, even though travel demand would change to respond to disruption.

This research recommended covering the whole subway networks through travel time assessment. Thus, this work will include not only the whole SMRA, but also related road networks in the SCA from a viewpoint of total social travel costs.

Uchida *et al.* (2015) suggested the optimal public transport service frequencies and link capacity expansions in a multimodal network that took into account car, transit, bus, and walking modes, to solve the network design problem, considering impacts from adverse weather conditions. A target of the suggested solution was “to minimise the sum of expected total travel time, operating cost of transit services, and construction cost of link capacity expansions under an acceptable level of variance of total travel time” (Uchida *et al.*, 2015, p.73). It was assumed that travellers’ route choice would be determined by the perceived expected travel disutility, with consideration of fare, in-vehicle travel time, waiting time, access/egress walking time, and discomfort from crowding.

Park *et al.* (2007) formulated a continuous network design problem (CNDP) with a travel time reliability constraint. The travel time reliability, the probability that a trip can be finished within a given time or level-of-service, was first estimated on the condition of the stochastic variation of link capacity. The authors applied a bi-level programming model to unravel the CNDP constrained with the travel time reliability and a genetic algorithm based on the penalty function method. “The upper-level problem is to minimise total travel time, satisfying the OD travel time reliability constraint which is set as a probabilistic constraint form. The lower-level problem is to formulate users' route choice behaviour following Wardrop's first principle" (Park *et al.*, 2007, p.496).

The research by Uchida *et al.* (2015) and Park *et al.* (2007) focused on the network design problem in adverse situations for travelling or with a specific criterion of travel time reliability, which have suggested a consideration of multi-modes in disrupted transport networks.

Berdica (2002) reviewed the past, present and future in the field of vulnerability as follows: What has been done, What is done, and What should be done. "Vulnerability problems have so far mostly been addressed in terms of isolated in-depth-studies of effects of individual emergency situations" Berdica (2002, p.123). After sporadic approaches in the initial studies, network reliability in transport modelling become important and increasing. For example, travel time reliability, terminal (connectivity) reliability and capacity reliability have been introduced as main performance metrics for road networks. Berdica (2002) asserted that vulnerability analysis should be integrated into all the different stages of the infrastructure process such as investment planning, optimisation of road maintenance, and operations management.

This research became one of important breakthrough for understanding the concept vulnerability in the field of transport and clarified diverse terminologies which are related to the vulnerability assessment: risk, serviceability, accessibility, resilience, robustness, and reliability. In addition, Berdica (2002) provided a comprehensive literature review and suggested clear directions for future research.

2.4 Stated Intentions Method

It is often necessary for transport planners to forecast impacts on travel demand of transport policies or disruptive events, such as construction of a new transport infrastructure, changing public transit fares, imposing road pricing schemes, or breakdown of public transit (Fujii and Gärling, 2003). Stated Preference (SP) was initially used in mathematical psychology and started being used extensively in transport in the 1980s, achieving important developments over the years (Luce and Tukey, 1964; Bates, 1988; Hensher, 1994; Louviere *et al.*, 2000; Ortúzar, 2000; Tudela and Rebolledo, 2006). Recent application of SP has been extended to the valuation of environmental assets (Bateman *et al.*, 2002; Rizzi and de Dios Ortúzar, 2003; Wardman and Bristow, 2004).

SP technique entails accumulating peoples' expressed preferences on hypothetical questions. SP methods require a purpose-designed survey for collection of their data. SP methods often use hypothetical choice scenarios in order to encourage individuals to express their preferences (Polak and Jones, 1997). Choosing one of the alternatives identifies the preferred attributes. The principle of Lancaster (1966) is applied to the process of choice, in that people choose an option because of its properties rather than for being that option *per se* (Tudela and Rebolledo, 2006).

The design of SP experiments is important. Orthogonal designs have been regarded as the key element in the SP technique, which mean that the attributes of questionnaires should not be correlated. However, the orthogonal conditions have been also criticised for realistic reasons as well as for the posterior usage of estimates (Kocur *et al.*, 1981; Fowkes and Wardman, 1988; Fowkes *et al.*, 1993; Louviere *et al.*, 2000).

The use of SP method can be justified from the perspective of microeconomic theory by the condition of invariance of the utility function. In other words, a utility function that determines choices of hypothetical alternatives is also applied to actual choices. However, it has been argued that real choices can be different according to the situation (Dawes, 1998; McFadden *et al.*, 1999). Different choices in a hypothetical situation and in a real situation have commonly been labelled as biased or anomalous (Kahneman *et al.*, 1991; Dawes, 1998). In order to remove bias and to accurately identify accurate choices based on SP data, some researchers have recommended that SP surveys be carefully designed so as to offer valid data (Smith, 1992; McFadden, 1998). Similarly, statistical methods have been proposed that will eliminate bias believed to result from the use of SP methods (Fujii and Gärling, 2003).

Fujii and Gärling (2003) labelled a preference determined by an invariant utility function as a *core preference* and a preference that depends on context as a *contingent preference*. Core preference is therefore assumed to influence not only actual behaviour but also stated survey choices. In SP methods, it is core preferences that researchers attempt to quantify as a utility function, by eliminating contingent preferences embedded in the SP data. However, it is doubtful whether actual choice always faithfully reflects core preferences, because core preferences themselves are impacted by attitude, which is the subjective evaluation of behaviour having a degree of favour or disfavour (Eagly and Chaiken, 1995). It is known empirically that attitude is mainly influenced by social pressure, personal norms, moral obligation, and perceived behavioural control. Therefore, attitude is often regarded as an inaccurate predictor of behaviour (Fishbein and Ajzen, 1975; Wood, 2000).

Clark and Toner (1997) suggested an optimisation scheme for an SP experiment. This consists of an initial setting of goals, a likelihood function with some prior coefficients, a likelihood evaluation, optimisation using the second derivatives matrix (Hessian matrix) and the variance-covariance matrix, and defining an objective function and its constraints. Carlsson and Martinsson (2003) used this procedure for the identification of a health attribute. In general, it is possible to achieve more significant estimates when using optimal designs than using classical designs. Furthermore, a smaller sample size is required to achieve similar statistical results (Tudela and Rebolledo, 2006).

Hensher (1994) listed three types of questionnaire that could be applied in SP studies: choice, ranking, and rating. A choice questionnaire is the simplest one; the respondent just chooses their favourable attributes in a hypothetical situation. The researcher assumes that the choices of respondents to the hypothetical situation are the same as their choice in the real world. A ranking questionnaire asks respondents to order the hypothetical situations in order of preference. A rating questionnaire requires respondents to not only list their responses in order of preference, but also to indicate how much they prefer each alternative to others (Ahern and Tapley, 2008).

Kroes and Sheldon (1988) elaborated the pros and cons of SP. It is easier to control the respondents in the SP method, since the researcher defines the conditions. Diverse variables that may not appear frequently in the Revealed Preference (RP) method are available in the SP approach. SP is also cheaper to apply because it can be done online, with multiple observations. However, people may not necessarily do what they say in the real situation, due to non-commitment bias or policy response bias. Kroes and Sheldon (1988) asserted that the combination of SP with RP can be a good alternative to solve this major problem of stated intention/revealed behaviour. Typically, "stated preference methods are used initially to estimate the trade-off ratios in the utility function, and then aggregate revealed preference data (for example, overall levels and shares) are used to scale the utility function and obtain a model which is consistent with the revealed preference data" (Kroes and Sheldon, 1988, p.13).

Wang *et al.* (2000) pointed out the limits of stated choice and stated preference methods. A respondent's ability to understand the hypothetical situations had a crucial influence on the choice of alternatives and it became a determinant in providing reliable answers. Wang *et al.* (2000) argued that if hypothetical situations are far removed from the respondent's daily experience, the stated preference study would result in poor models and inaccurate results. Therefore, stated preference studies should have some relation to the real world, which could be underpinned by revealed preference methods.

Swait *et al.* (1994) compared the advantages and disadvantages of RP and SP studies. They argued that an RP study could represent current market situations better than SP. In other words, the revealed outcomes were produced in real situations without any hypothetical conditions, which were dependent on the respondents' perceptions of attribute levels (Hensher, 1994). Compared to RP studies, SP studies were less constrained and allowed potential changes to be looked at (Swait *et al.,* 1994). SP studies allowed decision-making variation to be examined as different types and levels of questionnaire attributes were considered (Hensher, 1994).

In SP methods based on microeconomic theory, a survey serves as an instrument to observe stated preferences. An SP obtained from a survey, however, can also be interpreted as a stated behavioural intention. This is probably more likely the case when the survey question solicits a stated intention. Intention strength is a factor that increases the likelihood that an intention will be implemented (Fishbein and Ajzen, 1975; Sheppard *et al.*, 1988). Thus, the reason why a stronger intention is more likely to be implemented is in part because the plan for implementing the intention tends to be more realistic. It has been also demonstrated that a plan for implementing the intention increases the likelihood that the behaviour will performed (Gollwitzer, 1993; Gillholm *et al.*, 1999; Gillholm *et al.*, 2000).

Stated intentions method is a very simple form of stated preference method and it has several biases. Basically, stated intentions in the diverse trip choices may differ from the real ones. Sun and Morwitz (2010) pointed out three main reasons for differences between stated intentions and actual choices: (1) systematic biases in reports of stated intentions; (2) changes in explanatory variables, which cause true intentions to shift over time; (3) the imperfect correlation between intentions and action. It is usually believed that a survey of stated intentions may generate responses with significant biases such as policy response bias and justification bias and a large random element (Ben-Akiva and Morikawa, 1990).

According to Bamberg *et al.* (2003, pp. 175-176), "the intention was affected by three factors including attitude towards the behaviour, subjective norm and perceived behavioural control. The three rational determinants of intention are each based on underlying beliefs. Attitude towards the behaviour is determined by behaviour beliefs, which are the person's overall general feeling towards their behaviour. A subjective norm is determined by normative beliefs that are a person's perceptions, from people who are important to them, about how they should or should not behave. Perceived behavioural control is determined by beliefs about what behaviours are difficult or easy to perform."

However, stated intentions method can deal with extreme hypothetical situations and is suitable for short online surveys provided there is no danger of policy response bias. Attitudinal measures can reflect subjective or unobserved factors that are important in the travel decision process. Since they described individuals' feelings, perceptions, and intentions with respect to hypothetic transport situations, stated intentions method significantly improved the explanatory power of demand models. It is possible to take into account subjective factors like convenience, comfort, and safety in the process of transport choices (Couture and Dooley, 1981).

This thesis requires several intended choices of travellers when they have to respond to disruptive events on the SMRS: commuters' mode choice and route selection, information sources to provide details of disruptive events, and travellers' individual and socio-economic characteristics. Considering the online survey questions and depth of their analysis, it is appropriate to adopt stated intentions rather than SP in this work (Couture and Dooley, 1981).

2.5 Summary

By reviewing the literature of vulnerability assessment in the field of transport networks, it is possible to connect this work's research methodology with the literature review.

It was found that the integrated vulnerability assessment between different transport modes had not been studied. Most previous research has focused the vulnerability assessment in railway systems or road networks separately. It is important to identify the impact of a disruptive event of one transport mode on another transport mode because travellers may want to continue their trips by using alternative transport modes. This work specifically aims to assess the vulnerability of public transport networks with integrated analysis between the subway systems, the SMRS, and road networks in the SCA. It will be assumed that there is one disruptive event on the SRMS, without considering its cause. This work will identify not only a narrow influence of the incident on the SMRS, but also the consequential impact on the adjacent road networks.

A second important finding from the literature review is that most research had not taken into account the individuals' potential choices in the situation of disruptive events. They had paid attention to the topological relations between links and nodes, as well as transport functional characteristics, without considering a changing selection of transport modes due to partially suspended railway systems. Travellers' reactions are expected to be quite different to those in normal situations but it is difficult to identify exactly the choices travellers make when they encounter a disruptive event on the SMRS. The reason is that the frequency of disruptive event is rare and incidents happen irregularly. Therefore, this work tried to reflect the stated intentions of travellers by hosting an online survey in order to identify more precisely the impact of a disruptive event on the SMRS and affected road networks.

In summary, previous studies in the field of vulnerability assessment of transport networks have adopted two main approaches: integrating different transport modes and different networks, and reflecting travellers' preferred choices in the situation of unexpected disruptions on their major travelling routes and modes.

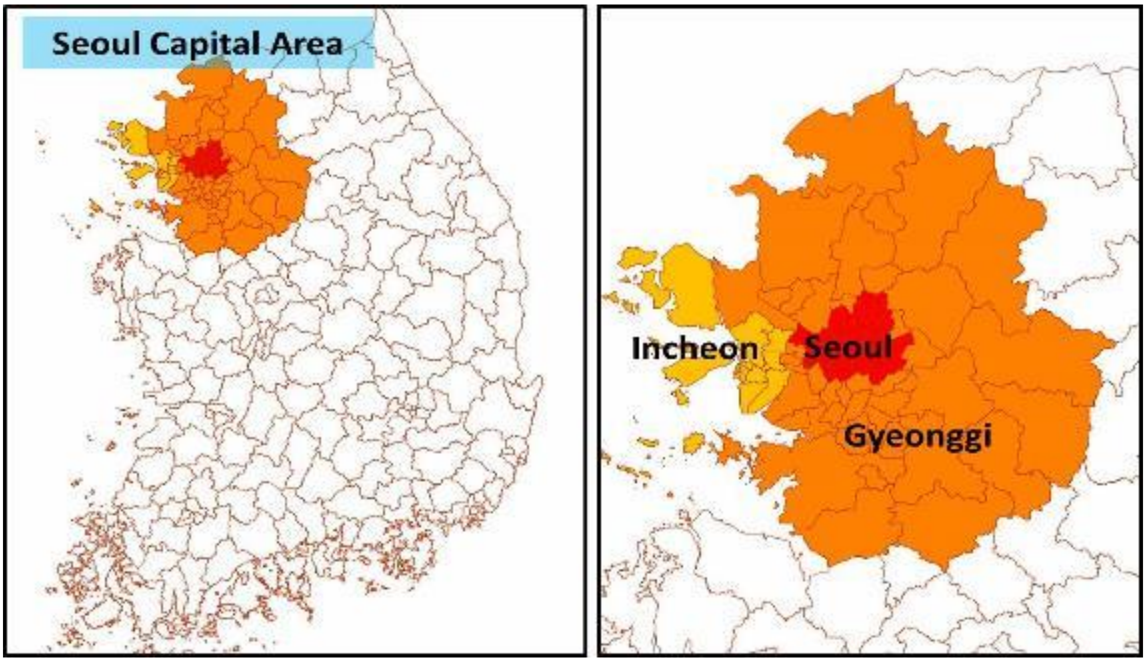
Chapter 3 Transport Networks in the Seoul Capital Area

3.1 Introduction

The SCA is the metropolitan area of Seoul, which is located in the north-west of South Korea. It is referred to as *Sudogwon* in Korean, similar to 'capital area', and contains three different administrative areas; Seoul Metropolitan City, Incheon Metropolitan City, and Gyeonggi Province (see Figure 3-1).

Seoul Metropolitan City is composed of 25 autonomous cities, while there are 10 autonomous cities in Incheon Metropolitan City. Gyeonggi Province, which has the greatest population in the country and the largest area of the three local governments in the SCA, consists of 31 autonomous cities or counties (See Appendix 4, Table A4-1, Table A4-2, Table A4-3).

Figure 3-1. Location of the Seoul Capital Area (SCA)



Source: TransCAD

The SCA has a population of 25.27 million (2015), comprising 49.5% of the nation's population, and is ranked as the second largest metropolitan area in the world. Its area is about 11,818 km^2, covering 11.8% of South Korea. The largest city is Seoul, with a population of 9.9 million people, followed by Incheon, with 2.90 million. Gyeonggi-do has a population of 12.48 million. By 2020, it is projected that more than 25.66 million people would live in the SCA. The importance of the SCA is revealed when it comes to economic indexes. While the Gross Regional Domestic Product (GRDP) of the SCA is £551.6 billion

(2015), the GRDP of the remaining 14 provinces is £565.3 billion. For centuries, the SCA has been the centre of South Korea from political, economic, social and cultural aspects.

The cities of the SCA are highly interconnected by road and rail. The 1st Seoul Ring Expressway is one of the most important trunk roads that connect satellite cities around Seoul: Ilsan, Toegyewon, Hanam, Bundang, Pangyo, Pyeongchon, Songnae, and Gimpo. The 2nd Seoul Ring Expressway will have been constructed by 2020. Almost every railroad line in Korea is connected through Seoul. The SMRS passes through Seoul and Incheon and most of the outlying cities within the SCA, has been serving a range of purposes. In addition, the region is a nexus for travel by air because the two largest Korean airports, Incheon International Airport and Gimpo Airport, are located in the metropolitan area.

Table 3-1. Population, Area, and GRDP of the SCA (2015)

Classification	**Population**	**Prop.**	**Area (km^2)**	**Prop.**	**GRDP** Billion KRW (Billion £)	**Prop.**
Whole Country	51,069,375	100%	100,295.35	100%	1,563,668 (1,116.9)	100.0%
Seoul	9,904,312	19.4%	605.25	0.6%	345,138 (246.5)	22.1%
Incheon	2,890,451	5.7%	1,040.88	1.0%	76,206 (54.4)	4.9%
Gyeonggi	12,479,061	24.4%	10,175.34	10.1%	350,963 (250.7)	22.4%
SCA	25,273,824	49.5%	11,818.71	11.8%	772,307 (551.6)	49.4%

Source: Korean Statistical Information Service, http://kosis.kr (adapted, 2017)

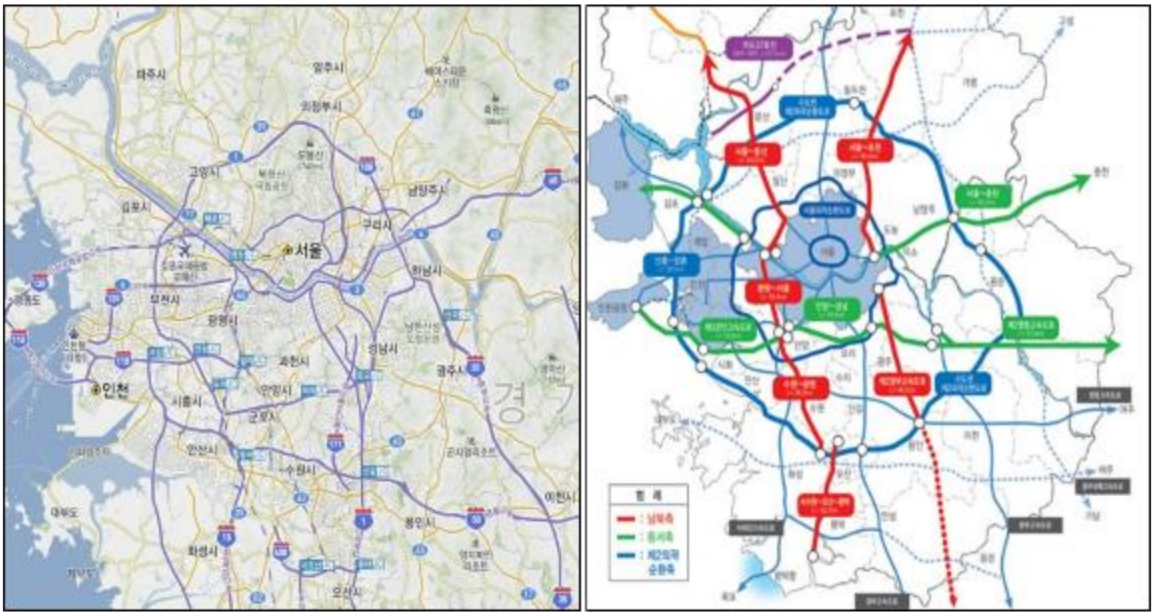
3.2 Transport Networks in the SCA

The SCA has been expanding its living area within 50 km aided by well-established trunk roads, highly linked subway networks, and metro bus for inter-cities that connect Seoul, Incheon metropolitan and Gyeonggi province. On the other hand, the continuous development of new towns, aiming at housing the influx of population from outside the SCA, has meant a difficult challenge to provide reliable and efficient transport networks.

According to the MOLIT (2007), the main transport strategy for the SCA is: construction of efficient trunk roads to solve chronically congested sections; establishment of effective public transport networks by focusing on the railway; and transportation demand management to reduce traffic volume.

Figure 3-2 (left) illustrates the current expressways around the SCA. The first remarkable one is Seoul Ring Expressway, a complete circle, which is called Expressway 100. It was fully completed in 2007 with the total length of 128 km, 100 km/h speed limit, and 4 lanes in each direction. Expressway 100 perfroms a crucial function in connecting neighbouring satellite cities around Seoul. Three major expressways, Gyeongbu (E1), Seohaean (E15) and Jungbu (E35) are in the north-south direction. In the east-west direction, Kyeongin (E120), 2nd Kyeongin (E110), Yeongdong (E50) and Gyeongchun (E60) Expressways stretch to the East coast.

Figure 3-2. Expressway of the Seoul Capital Area in 2015 (left) and in 2020 (right)



Source: google (adapted, 2016)

Figure 3-2 (right) represents a master plan for expressways in the SCA by 2020. The most noteworthy construction is the 2nd Seoul Ring Expressway (E400) and it is being completed to schedule. Also planned is the construction of two expressways in the north-south direction. They are the first to serve north-south in the northern Seoul area. Another possibility, not decided yet, is an underground trunk road network, because of the huge cost and the impossibility of widening current roads or constructing new roads due to existing houses and apartment blocks.

The other major infrastructure in the SCA is the subway system (SMRS), which is a typical public transit mode that can deliver many passengers with punctual operations. The subway system in the SCA covers Seoul, Incheon, Gyeonggi, part of Gangwon province, and Chungcheong province. 11 operators are in charge of 18 separate lines. Starting from a base 81.8 km in 1974, the total length of the SMRS surpassed 900 km in 2012 and is currently 1,014.4 km. There are 636 stations in the whole network (see Table 3-2). On completion of sections currently being constructed in 2020, the length would exceed 1,100 km.

Table 3-2. The Seoul Metropolitan Railway Systems

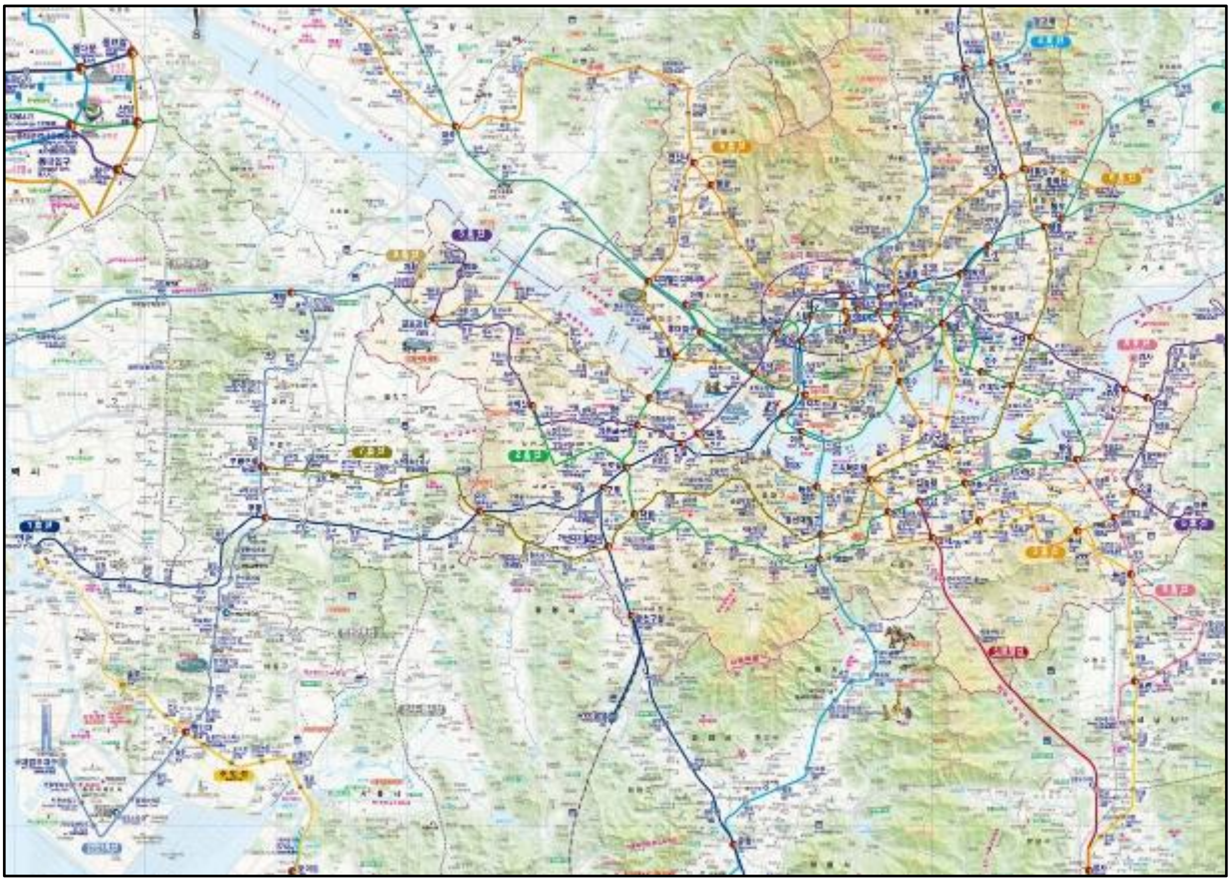
No.	Name	Stations	Length(km)	Lines
1	SMRS Line 1	98	200.6	Seoul Metro Line 1, Gyeongwon Line, Gyeongbu Line, Gyeongin Line, Gyeongbu Express Rail, Janghang Line
2	Seoul Metro Line 2	51	60.2	Seoul Metro Line 2
3	SMRS Line 3	44	57.4	Seoul Metro Line 3, Ilsan Line
4	SMRS Line 4	48	71.5	Seoul Metro Line 4, Gwacheon Line, Ansan Line
5	Seoul Metro Line 5	51	52.3	Seoul Metro Line 5
6	Seoul Metro Line 6	38	35.1	Seoul Metro Line 6
7	Seoul Metro Line 7	51	57.1	Seoul Metro Line 7
8	Seoul Metro Line 8	17	17.7	Seoul Metro Line 8
9	Seoul Metro Line 9	30	31.7	Seoul Metro Line 9
10	Gyeongui-Joongang Line	53	124.5	Gyeongui-Joongang Line
11	Gyeongchun Line	22	86.0	Gyeongchun Line, Joongang Line, Mangwoo Line
12	Boondang Line	36	52.9	Boondang Line
13	Suin Line	14	19.9	Suin Line
14	Incheon Metro Line 1	29	29.4	Incheon Metro Line 1
15	Incheon Airport Railway	12	58.0	Incheon Airport Railway
16	Shin Boondang Line	12	31.0	Shin Boondang Line
17	Uijeongbu Light Railway	15	10.6	Uijeongbu Light Railway
18	Yongin Light Railway	15	18.5	Yongin Light Railway

Source: Korea Railway Information Center, http://www.kric.or.kr (adapted, 2016)

To transfer between public transportation modes, a smart integrated fare system was introduced in July 2007. The metropolitan public transport fare system, intended to mitigate the economic burden and enhance the convenience of passengers, collects a fare in proportion to the distance, regardless of the means of public transport. Gyeonggi province, cooperating with Seoul and the Korea Railroad, were the first to adopt the system. From September 2008, it was extended to intercity bus and metro bus. And in October 2009, Incheon finally participated to the integrated public transport fare system. It means that now passengers can use every public transit mode with unified fare system.

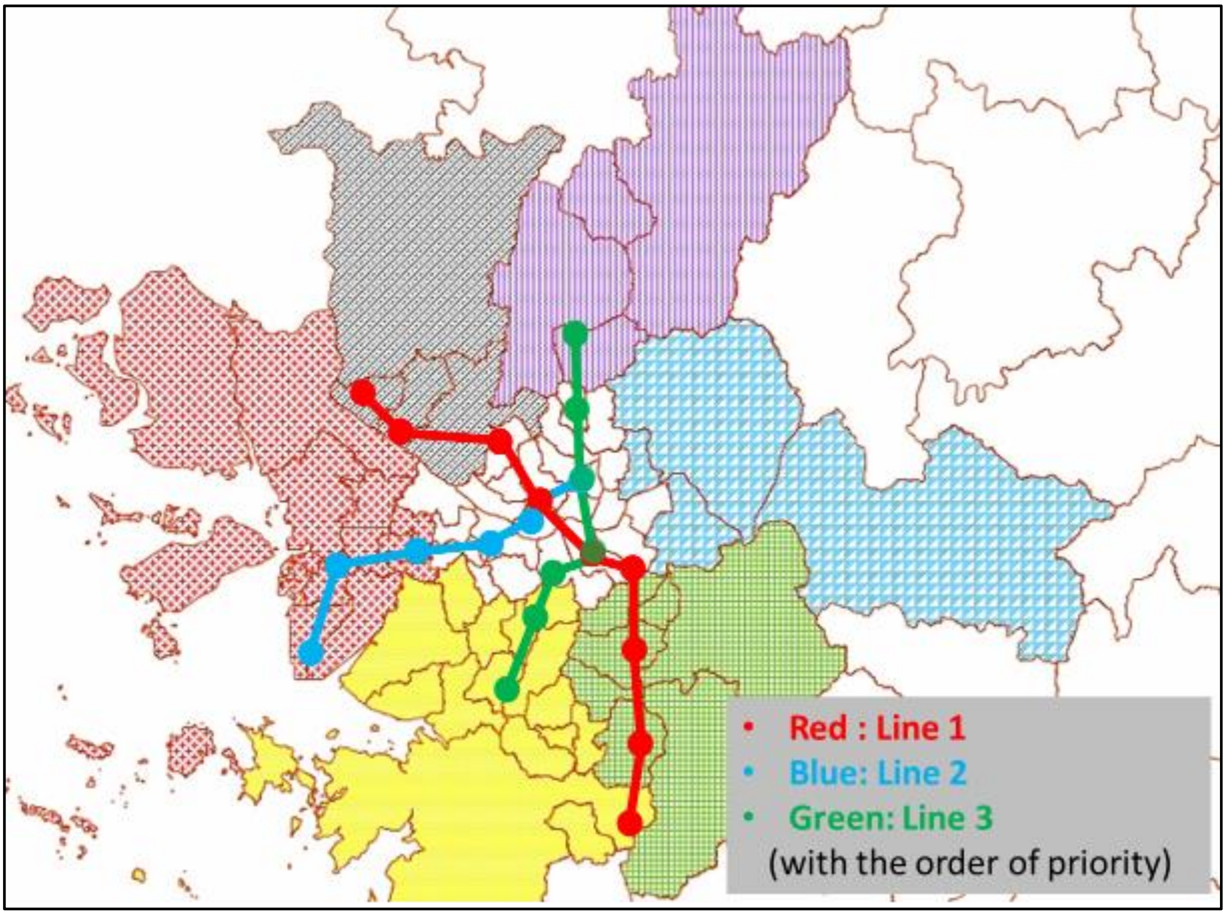
An innovative policy was introduced for the purpose of solving traffic congestion around the SCA: Metropolitan Express Railway (MER). As shown in Figure 3-3, the current railway systems have several curved lines so that average speed is only 30-40 km/h. MER is aiming at connecting transport hubs directly in the SCA (see Figure 3-4) with 100 km/h average speed (maximum operating speed 180 km/h) so that travel time reduces to less than 30% of current travel time. It will be constructed below a 50 m depth to overcome existing barriers. The purpose of MER is similar to that of RER in Paris and Crossrail in London.

Figure 3-3. The Seoul Metropolitan Railway Systems in the Seoul Capital Area



Source: google (adapted, 2016)

Figure 3-4. Future Plans of Metropolitan Express Railway



Source: MOLIT (adapted, 2016)

3.3 Car Ownership by Country

When travellers decide on their major transport mode for commuting to work, car availability as well as the provision of public transport service is an important factor. If a traveller does not own their own car, they have to use public transport even when the accessibility of public transport is not good or the cost is expensive. Thus, where the railway systems are disrupted, analysis of the alternative mode choice has a substantial relation to car ownership in a given country. Comparing car ownership in different countries can be useful when judging the usefulness of the analysis for broad applicability.

Table 3-3 shows the car ownership in 15 countries. South Korea shows a similar average car ownership to several developed countries like USA, Japan, Germany, Italy, France, UK, Spain, and Canada.

Table 3-3. Car Ownership by Country (Dec 2013)

Rank	Country	Car No.	Population (thousand)	Population/Car No.
1	USA	252,714,696	320,051	1.3
2	China	119,510,000	1,385,567	11.6
3	Japan	76,619,066	127,144	1.7
4	Russia	47,220,000	142,834	3.0
5	Germany	47,014,699	82,727	1.8
6	Italy	41,829,934	60,990	1.5
7	Brazil	39,695,000	200,362	5.0
8	France	38,200,000	64,291	1.7
9	UK	36,282,603	63,136	1.7
10	Mexico	34,379,555	122,332	3.6
11	India	32,499,000	1,252,140	38.5
12	Spain	27,154,604	46,927	1.7
13	Poland	22,734,000	38,217	1.7
14	Canada	22,333,794	35,182	1.6
15	Korea	19,400,864	50,220	2.6

Source: MOLIT (2014)

3.4 Commuting trip in the SCA

Generally speaking, commuting is one of the inevitable trips directly related to monthly or annual income. Therefore, commuters are very sensitive to commuting times, monetary costs and comfort of the commuting environment. These elements influence individual commuters financially, physically and psychologically. Commuting time is mainly a function of the specific region's socio-economic characteristics such as the residential distribution of commuters, working opportunities by number of employees, transport networks available to use, and so on.

Table 3-4. Purpose of Trips within the SCA in Trips/day (2014)

Trip Purpose	Origin \ Desti.	Seoul	Incheon	Gyeonggi	Outside of SCA	Total
Seeing Off	Seoul	161,696	2,480	10,715	273	175,164
	Incheon	2,812	44,853	2,765	41	50,472
	Gyeonggi	17,346	5,870	262,633	858	286,708
	Outside of SCA	151	0	887	-	1,038
	Subtotal	182,006	53,203	277,000	1,172	513,381
Returning Home	Seoul	8,929,398	258,864	1,847,270	69,049	11,104,581
	Incheon	137,791	2,221,827	244,434	17,594	2,621,645
	Gyeonggi	926,186	254,957	9,742,551	57,840	10,981,533
	Outside of SCA	116,340	24,979	167,029	-	308,349
	Subtotal	10,109,715	2,760,627	12,001,284	144,482	25,016,108
Going to Work	Seoul	3,999,110	90,581	605,673	24,029	4,719,393
	Incheon	179,857	893,726	181,737	3,318	1,258,637
	Gyeonggi	1,150,709	120,736	3,949,477	49,785	5,270,707
	Outside of SCA	8,416	1,044	31,044	-	40,503
	Subtotal	5,338,092	1,106,087	4,767,930	77,132	11,289,241
Going to School	Seoul	1,553,600	11,924	132,757	17,500	1,715,781
	Incheon	38,850	415,328	37,884	4,291	496,353
	Gyeonggi	193,873	15,960	1,913,003	41,212	2,164,048
	Outside of SCA	5,103	1,083	3,945	-	10,130
	Subtotal	1,791,426	444,295	2,087,589	63,002	4,386,312
Going to Private Educational Institute	Seoul	809,681	2,667	16,987	35	829,369
	Incheon	6,995	180,827	9,539	29	197,390
	Gyeonggi	62,143	3,561	891,506	317	957,527
	Outside of SCA	325	29	49	-	403
	Subtotal	879,143	187,084	918,081	381	1,984,689

Business	Seoul	2,084,136	54,748	285,938	84,214	2,509,036
	Incheon	42,750	387,545	75,598	16,779	522,672
	Gyeonggi	307,695	72,271	1,719,601	124,875	2,224,441
	Outside of SCA	74,042	17,197	112,122	-	203,361
	Subtotal	2,508,623	531,760	2,193,258	225,869	5,459,510
Shopping	Seoul	957,560	3,345	29,637	4,221	994,763
	Incheon	8,911	237,338	6,609	332	253,189
	Gyeonggi	70,495	7,594	869,286	2,952	950,327
	Outside of SCA	3,310	265	2,689	-	6,264
	Subtotal	1,040,276	248,542	908,221	7,504	2,204,543
Leisure	Seoul	3,120,166	24,859	247,791	112,945	3,505,761
	Incheon	35,622	654,846	53,906	17,100	761,474
	Gyeonggi	346,647	50,555	2,900,238	117,906	3,415,346
	Outside of SCA	107,509	30,888	98,422	-	236,819
	Subtotal	3,609,944	761,147	3,300,357	247,952	7,919,400
Total for all Purposes	Seoul	21,615,347	449,467	3,176,768	312,265	25,553,848
	Incheon	453,588	5,036,290	612,471	59,484	6,161,833
	Gyeonggi	3,075,094	531,504	22,248,294	395,745	26,250,637
	Outside of SCA	315,196	75,484	416,187	-	806,867
	Subtotal	25,459,225	6,092,745	26,453,720	767,494	58,773,185

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table 3-4 represents the trips in the SCA in 2014, by purpose: seeing off, returning home, going to work, going to school, going to private educational institute, business, shopping, and leisure. Returning home amounted to 25,016,108 trips per day, comprising 42.6% of the 58,773,185 total trips. In other words, about a half of all day trips were heading for home. Going to work was the most frequent purpose of outbound trip from home at 19.2% of the total trips at 11,289,241. Leisure trip was the second largest outbound trip from home at 7,919,400. Going to school in the morning was 7.5% of the total trips while going to private educational institute in the evening was 3.4%. Business trips clocked up 5,459,510, at 9.3%.

Table 3-5. χ^2 values of Seoul, Incheon, Gyeonggi, and Outside of SCA for Purpose Trips

Seoul	Incheon	Gyeonggi	Outside of SCA
53,116	20,538	79,323	551,341

χ^2 values for Seoul, Incheon, Gyeonggi, and Outside of SCA were calculated as seen in Table 3-5. χ^2 values were considerably high because the observed values of purpose trips. It is possible to say that purpose trips among regions are different. Especially, trips from the outside of SCA were considerably different characteristics, compared to other three regions.

The SCA has expanded due to the suburbanisation of residential areas. As a result of urban sprawl, long-distance commuting has continued to increase. The Korean government has adopted a new towns policy to solve the scarcity of housing around Seoul since the late 1980s. Consequently, the mismatch of location between home and work has been deteriorating for decades and commuting times have been getting longer, although diverse transport infrastructures have been newly constructed.

Table 3-6 illustrates the distribution of commuting time in the SCA. In 2010 for the whole of Korea commuters rose to 21.57 million, an increase of 25.4% since 2000. Although Seoul experienced a moderate growth of commuters, commuters from Gyeonggi and Incheon increased sharply in that decade. In the case of Gyeonggi, there was a rise of 1.63 million or 47.9%. In 2010, 1.15 million Seoul commuters (26%), commuted for longer than 1 hour. The average for the SCA was 24.5% of commuters, or 2.61 million, have to travel more than 1 hour to go to work.

Table 3-6. Distribution of Commuters in the SCA by Commuting Time

	Commuting Time (minutes)	2000		2010		Increasing Rate of Commuters (%)
		No. of Commuters	%	No. of Commuters	%	
Seoul	CT < 30	1,359,343	36.5	1,580,038	35.5	16.2
	30 ≤ CT < 60	1,472,280	39.5	1,724,300	38.7	17.1
	CT ≥ 60	897,643	24.1	1,152,044	25.9	28.3
	Subtotal	3,729,266	100.0	4,456,382	100.0	19.5
Incheon	CT < 30	403,719	44.2	508,912	43.2	26.1
	30 ≤ CT < 60	313,986	34.4	399,597	33.9	27.3
	CT ≥ 60	195,459	21.4	269,006	22.8	37.6
	Subtotal	913,164	100.0	1,177,515	100.0	28.9
Gyeonggi	CT < 30	1,632,385	48.1	2,300,996	45.9	41.0
	30 ≤ CT < 60	1,017,188	30.0	1,521,876	30.3	49.6
	CT ≥ 60	740,741	21.8	1,192,772	23.8	61.0
	Subtotal	3,390,314	100.0	5,015,644	100.0	47.9
Nationwide	CT < 30	9,571,178	55.7	11,641,068	54.0	21.6
	30 ≤ CT < 60	5,133,143	29.9	6,555,652	30.4	27.7

	Commuting Time (minutes)	2000		2010		Increasing Rate of Commuters (%)
		No. of Commuters	%	No. of Commuters	%	
	CT ≥ 60	2,491,392	14.5	3,374,375	15.6	35.4
	Subtotal	17,195,713	100.0	21,571,095	100.0	25.4

Source: Lee *et al.* (2012)

Commuters live more in the suburbs than central Seoul. Table 3-7 shows of the top 10 cities for commuters, 7 are located outside Seoul and 30% of all commuters in the SCA live in these 7 cities. By contrast, there are more jobs in central Seoul than the suburbs (See Table 3-8). For example, about 17.3% of all commuters in the SCA are working in the four autonomous districts of Seoul: Gangnam, Seocho, Yeongdeungpo, and Junggu. This phenomenon is a result of 46.2% of all companies in the SCA is located in Seoul.

Table 3-7. Top 10 Cities in the SCA by Number of Commuters living in the City (2010)

City	No. of Commuters	Proportion of SCA	Population	Proportion of SCA	No. of Employees	Proportion of SCA
Suwon	587,870	5.5	1,071,913	4.5	327,096	3.7
Seongnam	514,009	4.8	949,964	4	291,817	3.3
Goyang	485,204	4.6	905,076	3.8	228,894	2.6
Bucheon	454,954	4.3	853,039	3.6	245,531	2.8
Yongin	420,558	3.9	856,765	3.6	220,686	2.5
Ansan	402,588	3.8	728,775	3.1	255,507	2.9
Songpa, Seoul	365,455	3.4	646,970	2.7	255,881	2.9
Anyang	341,044	3.2	602,122	2.5	207,601	2.3
Nowon, Seoul	319,520	3.0	587,248	2.5	101,072	1.1
Gangnam, Seoul	314,126	2.9	527,641	2.2	640,954	7.2
Total	4,205,328	39.4	7,729,413	32.5	2,775,039	31.3

Source: Lee *et al.* (2012)

Table 3-8. Top 10 Cities in the SCA by Number of Commuters working in the City (2010)

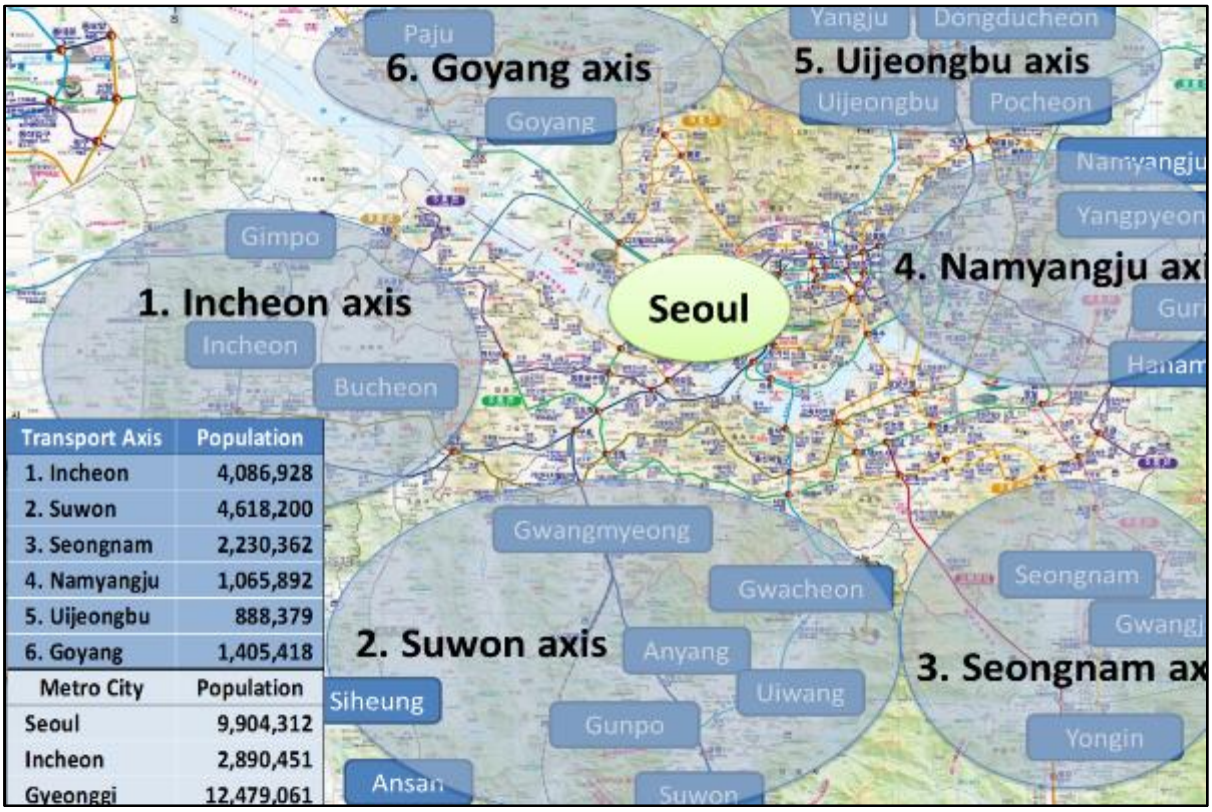
City	No. of Commuters	Proportion of SCA	Population	Proportion of SCA	No. of Employees	Proportion of SCA
Gangnam, Seoul	747,479	7.0	527,641	2.2	640,954	7.2
Suwon	505,883	4.8	1,071,913	4.5	327,096	3.7
Seongnam	428,368	4.0	949,964	4.0	291,817	3.3
Ansan	392,013	3.7	728,775	3.1	255,507	2.9

City	No. of Commuters	Proportion of SCA	Population	Proportion of SCA	No. of Employees	Proportion of SCA
Seocho, Seoul	385,422	3.6	393,270	1.6	401,917	4.5
Goyang	368,413	3.5	905,076	3.8	228,894	2.6
Junggu, Seoul	358,366	3.4	121,144	0.5	380,349	4.3
Yeongdeungpo, Seoul	355,725	3.3	396,243	1.7	326,410	3.7
Yongin	353,526	3.3	856,765	3.6	220,686	2.5
Hwaseong	338,797	3.2	488,758	2.1	231,810	2.6
Total	4,233,962	39.8	6,439,549	27.1	3,305,440	37.3

Source: Lee *et al.* (2012)

The axis of commuting route in the SCA will now be addressed. Since Seoul is at the centre of the SCA and there are many job opportunities, many commuters from satellite cities make the trip to go to work (see Figure 3-5). Although the population of satellite cities (as of 2015) is small compared to Seoul, there have been increasing numbers of commuters from the outer areas into Seoul.

Figure 3-5. Six Transport Axes around Seoul



Source: google, Korean Statistical Information Service (http://kosis.kr) (adapted, 2017)

Table 3-9 shows the data on the six transport axes. They are divided by the location of main subway/railway lines, considering primarily not the city population but geographically. Uijeongbu axis has the smallest population of the six axes.

Table 3-9. Six Transport Axes around the Seoul Capital Area (2015)

No.	Name	Cities Served	Population	SMRS
1	Incheon	Incheon Bucheon Gimpo	4,086,928	SMRS Line 1, Seoul Metro Line 7, Incheon Metro Line 1, Incheon Airport Railway
2	Suwon	Suwon, Ansan Siheung, Hwasung Osan, Gunpo, Uiwang Anyang, Gwangmyeong Gwacheon	4,618,200	SMRS Line 1, SMRS Line 4, Suin Line, Boondang Line
3	Seongnam	Seongnam Yongin Gwangju	2,230,362	SMRS Line 3, Seoul Metro Line 8, Boondang Line, Shin Boondang Line
4	Namyangju	Namyangju Yangpyeong Guri Hanam	1,065,892	Seoul Metro Line 5, Seoul Metro Line 8, Gyeongui-Joongang Line, Gyeongchun Line
5	Uijeongbu	Uijeongbu, Yangju Pocheon, Dongducheon	888,379	SMRS Line 1, SMRS Line 4, Seoul Metro Line 7
6	Goyang	Goyang Paju	1,405,418	SMRS Line 3, Gyeongui-Joongang Line

Source: google, Korean Statistical Information Service http://kosis.kr (adapted, 2017)

Table 3-10 shows that there was a considerable increase in commuting trips between 2002 and 2006, but the rate became sluggish thereafter. This is because neighbouring cities have started to become self-contained cities.

Table 3-10. All Trips from Outside Seoul into Seoul in Trips/day

Axis	2002	2006	2010	2011	2012	2013	Ave. Increase Rate
Incheon	453,672	493,497	512,257	541,581	566,909	573,620	26.4%
Suwon	538,080	621,694	597,986	616,800	605,621	615,414	14.4%
Seongnam	352,496	397,558	391,942	404,642	415,994	421,646	19.6%
Namyangju	248,544	327,497	323,938	341,108	327,667	340,798	37.1%
Uijeongbu	134,712	174,818	163,517	168,312	163,198	167,034	24.0%

Goyang	233,957	313,368	289,315	295,964	300,779	307,953	31.6%
Subtotal	1,961,461	2,328,432	2,278,955	2,368,407	2,380,168	2,426,465	23.7%

Source: 2014 Revision of Origin/Destination Data in the Seoul Capital Area (adapted, 2016)

In contrast, similar trips for commuting from outside of Seoul into Seoul, have continuously risen for 10 years. Table 3-11 demonstrates that Incheon axis, Suwon axis, and Seongnam axis have experienced high inflow to Seoul. The Namyangju axis showed the highest increasing rate in the same period.

Table 3-11. Commuting to Work Trips from Outside Seoul into Seoul in Trips/day

Axis	2002	2006	2010	2011	2012	2013	Average Increase Rate
Incheon	253,958	253,165	296,784	312,123	337,899	330,147	30.0%
Suwon	282,671	313,588	332,887	341,977	345,788	342,164	21.0%
Seongnam	182,832	209,813	221,325	226,877	238,509	232,487	27.2%
Namyangju	117,789	146,582	157,472	168,776	166,021	168,590	43.1%
Uijeongbu	70,293	89,826	81,918	83,914	84,200	83,434	18.7%
Goyang	124,119	161,222	163,318	164,817	167,111	166,478	34.1%
Subtotal	1,031,662	1,174,196	1,253,703	1,298,484	1,339,526	1,323,300	28.3%

Source: 2014 Revision of Origin/Destination Data in the Seoul Capital Area (adapted, 2016)

Data from Table 3-10 and Table 3-11 shows all trips and commuting trips by travel axis on a normal day, with normal congestion. In the case of disruptions on any related subway networks, the result will be considerably different, which will be shown in this study.

3.5 Disruptive Events on the SMRS

Table 3-12 shows all major disruptive events on the SMRS since 1998. The criterion for selection is an event lasting an hour or more. Causes of disturbances to the SMRS were diverse, including maintenance problems, train accidents, impacts of mishaps near SMRS stations or railways, and natural disasters such as flooding, ground subsidence, and snow storm.

The longest event was the flooding of Taereung Station from Joongrangcheon on 2 May 1998. This flooding affected 18 stations from Dobongsan Station to Keonkuk University Station of the Seoul Metro Line 7 for more than 9 days. Another flooding of Seoul Metro Line 7 blocked 14 stations (from Cheongdam to Boramae) on 15 July 2001. The stations were closed for 2 days 14 hours. Ground subsidence at Gajwa Station of Gyeongui-Joongang Line brought 4 days' closure of 5 stations from Susak to Seoul in June 2006. Land sliding toward SMRS Line 1 between Seongbuk Station and Dobongsan Station was another natural disaster, which continued for 4 hours on 29 June 2011.

In the field of maintenance, electricity cuts to a train were the most frequent cause for disorder on the SMRS followed by train problems. Electricity cuts and train malfunction were solved relatively quickly compared to other causes. Train crash is an exceptional event but makes a substantial impact to the SMRS when it happens. The train crash, which occurred at Sangwangsimni Station on Seoul Metro Line 2 on 2 May 2014, caused the suspension of 10 stations for 11 hours. Lastly, interference from outside SMRS facilities can stop the operation of the railway. For example, overturning of a crane at a construction site near the railway at Bupyeong Station had blocked 14 stations of SMRS Line 1 for 15 hours on 16 Sep 2015.

Table 3-12. Major disruptive events on the SMRS

No.	Occurred		Resolved		Duration	Line	Disrupted Section (Station/Direction): Causes
	Date	Time	Date	Time			
1	02/05/1998	07:40	11/05/1998	17:00	9 days 10 h	7	Dobongsan - Keonkuk Univ.: Flooding of Taereung Station from Joongrangcheon
2	20/06/1998	20:11	20/06/1998	21:30	1.3 h	4	Sanbon-Namtaeryeong: Electricity cut to a train at Namtaeryeoung Station
3	06/08/1998	05:30	06/08/1998	16:00	10.5 h	7	Jangam-Keonkuk Univ.: Flooding of Dobongsan Station
4	08/08/1998	17:50	09/08/1998	05:30	12 h	7	The whole of Line 7: Flooding forecast for Joongrangcheon
5	15/07/2001	05:30	17/07/2001	20:00	2 days 14h	7	Cheongdam-Boramae: Flooding

No.	Occurred		Resolved		Duration	Line	Disrupted Section (Station/Direction): Causes
	Date	Time	Date	Time			
6	26/12/2002	21:20	26/12/2002	23:20	1 h	1	Incheon-Bupyeong: Electricity cut to a train at Dohwa Station
7	03/01/2005	07:10	03/01/2005	10:45	3.5 h	7	Shinpung-Onsu: Arson in a train
8	23/02/2005	07:30	23/02/2005	08:20	1 h	Bundang	Seolleung-Bojeong: Train failure at Moran Station
9	03/06/2006	17:15	07/06/2006	18:00	4 days	Gyeongui	Susak-Seoul: Ground subsidence at Gajwa Station
10	06/06/2005	10:36	06/06/2005	13:00	2.3 h	4	Geumjeong-Government Complex Gwacheon: Electricity cut at Geumjeong Station
11	12/06/2006	06:52	12/06/2006	07:45	1 h	4	Dangogae-Sadang: Electricity cut at Nowon Station
12	12/07/2006	05:30	13/07/2006	05:17	1 day	3	Daehwa-Jichuk: Flooding of Jeongbalsan Station
13	27/12/2006	15:17	27/12/2006	18:25	1 h	1	Changdong-Soyosan: Electricity cut between Ganeung Station and Deokjeong Station
14	14/08/2008	05:54	14/08/2008	07:50	2 h	7	Onsu-Cheonwang: Train derailment at Cheonwang Station
15	06/07/2009	08:17	06/07/2009	15:00	7 h	2	Seoul-Yongsan (1, Gyeongbu, Gyeongui): Overturning of a crane near railway near Chungjeongro Station
16	20/01/2010	20:05	20/01/2010	21:50	1.6 h	2	Sindorim-Hongik Univ.: Failure of rail converter at Sindorim Station
17	22/01/2010	13:15	22/01/2010	16:04	3 h	1	Incheon-Bucheon: Overturning of a ladder truck near railway near Dongam Station
18	02/09/2010	05:20	02/09/2010	09:55	4.5 h	1,4	Incheon-Seoul, Ansan-Sanbon: Electricity cut due to a typhoon
19	21/09/2010	16:30	21/09/2010	20:20	4 h	4	Seoul-Sadang: Flooding of Sinyongsan Station
20	21/09/2010	15:50	21/09/2010	18:32	3 h	1	Incheon-Guro: Flooding of Oryudong Station
21	09/11/2010	06:05	09/11/2010	10:45	4.5 h	4	Sanbon-Ansan: Electricity cut between Sanbon Station and Ansan Station
22	06/06/2011	04:25	06/06/2011	09:10	5 h	1	Guro-Suwon: Overturning of a boring machine in underpass construction site near railway
23	29/06/2011	13:00	29/06/2011	18:10	5 h	1	Seongbuk-Dobongsan: Landsliding near railway
24	27/07/2011	06:05	27/07/2011	10:15	4 h	1	Incheon-Guro: Flooding of Oryudong Station
25	23/09/2011	06:46	23/09/2011	07:57	1 h	Jungang	Yongmun-Yongsan: Electricity cut to a train at Yangwon Station

No.	Occurred		Resolved		Duration	Line	Disrupted Section (Station/Direction): Causes
	Date	Time	Date	Time			
26	26/09/2011	07:00	26/09/2011	08:05	1 h	Gyeongui	Haengsin-Sinchon: Electricity cut between Haengsin Station and Sinchon Station
27	02/02/2012	07:22	02/02/2012	11:52	4.5 h	1	Yongsan-Hoegi: Electricity cut and train derailment during towing the train
28	15/08/2013	06:15	15/08/2013	08:30	2.2 h	7	Taereung-Cheongdam: Train failure near Keonkuk Univ. Station
29	15/10/2013	06:28	15/08/2013	10:40	4 h	4	Sanbon-Ansan: Train disorder at Banwol Station
30	06/01/2014	05:40	06/01/2014	07:40	2 h	4	Oido-Seonbawi: Electricity cut between Geumjeong Station and Gacheon Station
31	03/04/2014	05:12	03/04/2014	10:25	5 h	4	Seoul-Sadang: Train derailment at Samgakji Station
32	02/05/2014	15:32	03/05/2014	02:42	11 h	2	Seongsu-Euljiro1-ga: Train crash at Sangwangsimni Station
33	30/07/2014	10:00	30/07/2014	12:14	2 h	1	Incheon-Seoul: Fire at Guro Station
34	20/11/2014	13:50	20/11/2014	14:50	1 h	4	Danggogae-Hanseong Univ.: Electricity cut at Danggogae Station
35	08/05/2015	07:00	08/05/2015	08:02	1 h	4	Sadang-Seoul: Electricity cut at Isu Station
36	08/07/2015	14:00	08/07/2015	17:20	3 h	1	Uijeongbu-Changdong: A demonstration on a crane at Dobongsan Sation
37	13/07/2015	21:50	13/07/2015	22:30	0.7 h	Bundang	Direction for Budang: Train failure at Bokjeong Station
38	16/09/2015	14:30	17/09/2015	05:00	15 h	1	Incheon-Bucheon: Overturning of a crane near railway near Bupyeong Station
39	16/10/2015	17:45	16/10/2015	18:15	0.5 h	1	Direction for Dongducheon: Train disorder at Jongno3-ga Station
40	09/11/2015	18:00	09/11/2015	18:55	1 h	1	Direction for Incheon: Train disorder at Seokgye Station
41	26/11/2015	01:50	26/11/2015	07:00	6 h	4	Dangogae-Seongshin Univ.: Fire in a maintenance car

Source: http://www.kric.or.kr, http://news.naver.com/

These 41 major disruptive events on the SMRS can be classified into four categories: facility problems, train problems, natural disasters, and accidents from external to the SMRS.

Facility problems include electricity supply disruptions to trains, fire at the stations, failure of rail converter, and fire in a maintenance car. The most frequent cause of the facility problems was electricity cuts, totalling 13 cases out of 16 disruptive events. If a facility problem occurs, the disrupted situation was resolved on average within 2.2 hours. Because there were 16 disruptive events between 20/06/1998 and 26/11/2015, the frequency of this kind disruption might be calculated as 398 days on average (see Table 3-13).

Table 3-13. Classification of Major disruptive events on the SMRS – Part 1

Facility Problems (Station, Electricity, Rail, ...)			Train Problems (Clash, Derailment, …)		
No.	Date	Duration	No.	Date	Duration
2	20/06/1998	1.3 h	7	03/01/2005	3.5 h
6	26/12/2002	1 h	8	23/02/2005	1 h
10	06/06/2005	2.3 h	14	14/08/2008	2 h
11	12/06/2006	1 h	28	15/08/2013	2.2 h
13	27/12/2006	1 h	29	15/10/2013	4 h
16	20/01/2010	1.6 h	31	03/04/2014	5 h
18	02/09/2010	4.5 h	32	02/05/2014	11 h
21	09/11/2010	4.5 h	37	13/07/2015	0.7 h
25	23/09/2011	1 h	39	16/10/2015	0.5 h
26	26/09/2011	1 h	40	09/11/2015	1 h
27	02/02/2012	4.5 h			
30	06/01/2014	2 h	Sum: 10	Freq.*: 396 days	Average: 3.09 h
33	30/07/2014	2 h	Unavailability Rate		0.3250/1,000
34	20/11/2014	1 h			
35	08/05/2015	1 h			
41	26/11/2015	6 h			
Sum: 16	Freq.*: 398 days	Average: 2.15 h		Freq.* means frequency of events over time	
Unavailability Rate		0.2251/1,000			

Train problems cover train failure, train crash, train derailment, and arson on a train. Train failure was the highest frequency in this criterion, occurring 6 times out of 10 events. The average frequency of train problem was 396 days and a disruptive event continued for 3.1 hours (see Table 3-13).

Natural disaster flooding was the most frequent cause of stoppage among various natural disasters. The SMRS is vulnerable to flooding due to its low elevation. Average duration of this kind of disruption was 44.7 hours and the frequency of natural disasters was 483 days (see Table 3-14).

Table 3-14 also shows that external accidents from outside could also stop normal operation of the SMRS. The most frequent type of external accident was blocking the railway by construction equipment near the SMRS. Recovery time for external accidents was longer than that of facility problems or train problems.

Table 3-14. Classification of Major disruptive events on the SMRS – Part 2

Natural Disasters (Flooding, Land Sliding, …)			External Accidents outside of the SMRS		
No.	Date	Duration	No.	Date	Duration
1	1998-05-02	9days 10 h	15	2009-07-06	7 h
3	1998-08-06	10.5 h	17	2010-01-22	3 h
4	1998-08-08	12 h	22	2011-06-06	5 h
5	2001-07-15	2 days 14h	36	2015-07-08	3 h
9	2006-06-03	4 days	38	2015-09-16	15 h
12	2006-07-12	1 day			
19	2010-09-21	4 h	Sum: 5	Freq.*: 453days	Average: 6.60h
20	2010-09-21	3 h		Unavailability Rate	0.6076/1,000
23	2011-06-29	5 h			
24	2011-07-27	4 h			
Sum: 10	Freq.*: 483days	Average: 44.65h		Freq.* means frequency of events over time	
	Unavailability Rate	3.8486/1,000			

If unavailability rate is defined as the duration of the disruptive events divided by the frequency of the disruptive events, see Equation 3-1, the unavailability of natural disasters is the highest, calculated as 3.8486/1,000. This means that the SMRS is not available for about 3.8 days out of 1,000 days due to the natural disasters.

$$Unavailability\ Rate = \frac{Duration_{dis.}}{Frequency_{dis.}} \tag{3-1}$$

where

$Duration_{dis.}$: duration of disruptive events on the SMRS in days
$Frequency_{nor.}$: frequency of disruptive events on the SMRS in days

Using the information of real disruptions, some lessons can be extracted for the imaginary scenario of disruptive events on the SMRS. First, many adjacent stations can be affected by a disrupting event on a specific station or a part of railway because of characteristics of railway or subway systems: impossibility of U-turn, rare sidings for escape and fixed routes. If a transfer station is disabled, the impact would be magnified in proportion to the number of connected lines. Second, time to recover normal operation is long compared to accidents on road networks. The reasons for long recovery are electricity supply, signal control, heavy trains, fixed rails, and so on. Third, the operational organisation can be unclear. Since local governments are in charge of construction and operation of metro systems in the SCA, affected sections may be divided by the boundary of metropolitan cities. For private investment projects, operational systems can be considerably different to those of public-operated railways.

From the features of the SMRS, hypothetical scenarios of disruptions on the six transport axes can be posited, see Table 3-15. A more detailed introduction to this scenario is covered later.

Table 3-15. Scenario of Disruptions on the SMRS on the Six Transport Axes

Transport Axis	Disrupted Section	No. of Stations	Duration	SMRS
1st Incheon	Incheon-Onsu	17	1 day	SMRS Line 1
2nd Suwon	Oido-Sadang	24	1 day	SMRS Line 4
3rd Seongnam	Suwon-Suseo	25	1 day	Boondang Line
4th Namyangju	Yongmun-Mangwoo	17	1 day	Gyeongui-Joongang Line
5th Uijeongbu	Soyosan-Dobongsan	14	1 day	SMRS Line 1
6th Goyang	Daehwa-Gupabal	12	1 day	SMRS Line 3

3.6 Traffic Zone Data

Traffic analysis zones are usually constructed using census block information in transport planning models because socio-economic data are provided by census block. The most frequently used information is the number of cars per household, household income, and employment within zones. This information helps to understand trips that are produced and attracted within the zone.

Table 3-16 shows the traffic analysis zones within the SCA and outside it. Since the main purpose of the analysis is an assessment of the integrated vulnerability of transport networks in the SCA, traffic zones within the SCA should be detailed by census block or the lowest hierarchy in the administrative district. However, cities located outside the SCA are divided into 1 traffic zone per city, in order to decrease the burden of calculation. In addition, traffic flows from outside the SCA into the SCA are relatively small compared to those within the SCA. Therefore, the SCA is minutely divided up with 1,107 traffic zones, and outside the SCA is roughly split into 130 traffic zones.

Table 3-16. Traffic Analysis Zone in the Seoul Capital Area

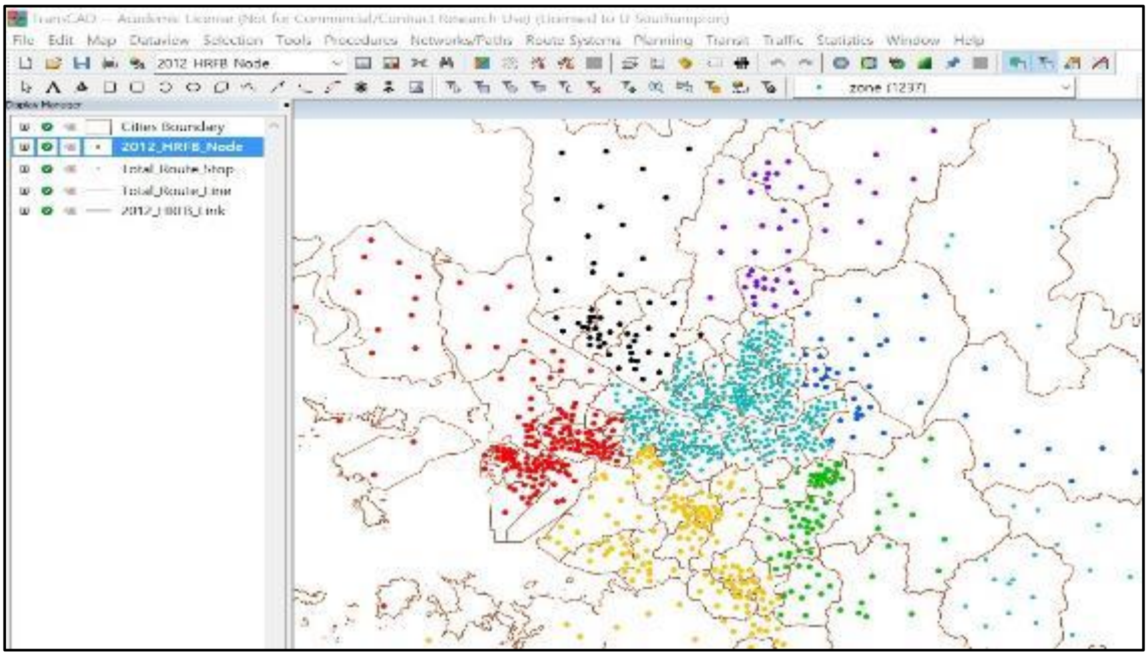
Transport Axis	City	TAZ ID	No. of TAZs	Subtotal
0 Seoul	Seoul	1-424	424	424
1st Incheon	Incheon	425-566	142	189
	Bucheon	700-736	37	
	Gimpo	1,002-1,011	10	
2nd Suwon	Suwon	567-605	39	180
	Ansan	785-809	25	
	Siheung	884-898	15	
	Hwaseong	1,012-1,034	23	
	Osan	878-883	6	
	Gunpo	899-909	11	
	Uiwang	910-915	6	
	Anyang	669-699	31	
	Gwangmyeong	737-754	18	
	Gwacheon	849-854	6	
3rd Seongnam	Seongnam	606-653	48	89
	Yongin	926-956	31	
	Gwangju	1,035-1,044	10	
4th Namyangju	Namyangju	863-877	15	45
	Yangpyeong	1,096-1,107	12	
	Guri	855-862	8	

Transport Axis	City	TAZ ID	No. of TAZs	Subtotal
	Hanam	916-925	10	
5th Uijeongbu	Uijeongbu	654-668	15	48
	Pocheon	1,056-1,069	14	
	Yangju	1,045-1,055	11	
	Dongducheon	777-784	8	
6th Goyang	Goyang	810-848	39	55
	Paju	957-972	16	
Seoul Capital Area (SCA)		1-1,107	1,107	1,107
Outside SCA		1,108-1,237	130	130
Nationwide		1-1,237	1,237	1,237

Source: 2014 Revision of Origin/Destination Data in the Seoul Capital Area (adapted, 2016)

Seoul comprises 424 traffic zones with an average population per zone of 23,828. Incheon has 142 traffic zones and is the 2nd largest city in the SCA with subtotal for Incheon axis of 189. The Suwon axis is made up of 10 cities with subtotal of 180. Subtotals of traffic zones for 3rd, 4th, 5th and 6th transport axes are 89, 45, 48 and 55 respectively. Traffic analysis zones are plotted on the map in Figure 3-6. Red dots, yellow dots green dots, blue dots, purple dots and black dots represent six transport axes area individually. Sky-blue dots mark traffic analysis zones in other areas including Seoul.

Figure 3-6. Traffic Zones

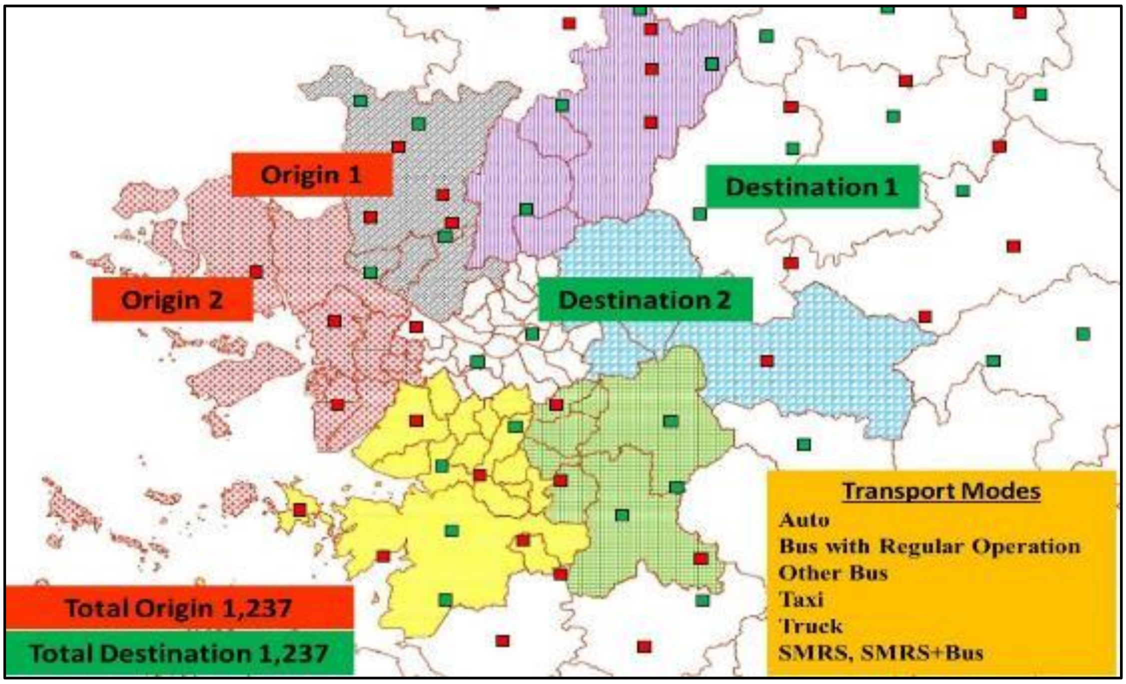


3.7 Origin/Destination Data in Normal Situations

Origin is the starting point at which travelling begins and destination is the end point at which travelling finishes. All 1,237 traffic zones can be both origins and destinations. Thus, the Origin/Destination (O/D) matrix for one transport mode is an array with 1,237 rows and 1,237 columns. O/D data can comprise different criteria according to travel purpose, transport mode, and time period. The O/D of purposes may be set up with: seeing-off, returning home, going to work, going to school, going to private educational institute, business, returning to office, shopping, and leisure. The O/D of transport modes can be set up with: car, bus with scheduled operation, another bus, taxi, truck, subway, motorbike, bike, and walking. The O/D of time period can be set up with: one-day, morning peak, evening peak, and so on.

Since the main purpose here is to calculate the impact of disruptive events on transport networks by determining the change in travel time, it is meaningless to distinguish each travel purpose. Our assumption is that disruptive events continue for 1 day. Consequently, O/D data for peak period is not required. This study will use six transport modes: car, bus with the scheduled operation, another bus, taxi, truck, and the SMRS (including transfer between the SMRS and bus). The O/D data for the normal situation are taken from the 2014 Revision of Origin/Destination Data in Seoul Capital Area (Seoul Metropolitan Transportation Association, 2015).

Figure 3-7. Origin/Destination with Six Transport Mode



3.8 Transport Networks Data

Transport networks mainly comprise road networks and transit networks. Road networks are for car, another bus, taxi, and truck. There is no pre-determined schedule for these four modes and all links can be used to make the total travel cost lower. By contrast, transit networks are operated with fixed routes and timetables. Therefore, basic data for road networks and transit networks are different.

3.8.1 Road Networks

Road networks can by represented by nodes and links. Nodes are the intersections of the roadways and each node is allocated a distinctive ID number. Conversely, each link has two ends with unique two node numbers. A roadway is defined by the links along its path (Edwards, 1992).

The 2014 Revision of Origin/Destination Data in the Seoul Capital Area (Seoul Metropolitan Transportation Association, 2015), listed 36,524 nodes in the road networks, and this work will use the same node data. ID of the node, x and y coordinates by UTM WGS 1984, are essential data and some supplementary data are attached. Figure 3-8 illustrates entire nodes of road networks with grey dots. Although the location of each node can be determined by its x and y coordinates, there is no information related to travelling characteristics such as a number of flows, average speed or degree of congestion.

However, link data can provide much information about travelling from origin to destination. Starting node and finishing node give the location of a specific link. Reversing starting node and finishing node with the same node IDs means the opposite transport flows. All roads, except one-way roads, have direction defined by the starting node and finishing node. The length of links and lanes of links are also basic material to define the characteristics.

This main information about links is closely related to travel flows and speeds. Parameters of the volume-delay function (VDF) for each link express how much congestion there is when specific traffic flows through the link. A classic VDF is the Bureau of Public Roads (BPR) Function, determined by BPR α and BPR β, free flow speed and capacity of the link. These parameters vary with the classification of the road[3], the location of road (urban or rural), the density of traffic signals, and number of lanes.

Figure 3-9 shows a partial map of the 51,170 links to be used in this study. Characteristics of each link are sourced from the 2014 Revision of Origin/Destination Data in Seoul Capital Area (Seoul Metropolitan Transportation Association, 2015).

3.8.2 Transit Networks

Vuchic (2007) argued that transit modes mostly exhibit two characteristics: right-of-way (ROW), and system technology. Right-of-way (ROW) is a physical surface on which the transit vehicles are operated and ROW comes in three flavours: Category A is a fully-controlled ROW in which a specific transport mode uses the way exclusively. Contrarily, Category C allows mixed travelling among different traffic modes. Category B has an intermediate ROW between Category A and C.

Table 3-17. Transit Classification

Tech. / ROW	Highway Driver-steered	Rubber-tyre guided, Partially guided	Rail	Specialised
C	Paratransit Shuttle bus Scheduled bus	Trolleybus	Streetcar Tramway Cable car	
B	Bus rapid transit	Guided bus	Light rail transit	
A	Bus in bus only lane	Rubber-tyred metro Rubber-tyred monorail Automated guided transit	Light rail rapid transit Rail rapid transit Metro Regional rail Commuter rail	Cog railway Funicular Aerial tramway

[3] In Korea: national expressway, national road, special metropolitan city road/metropolitan city road, provincial road, municipal/county/district road. (http://www.law.go.kr/eng/engMain.do, article 10 of the Road Act)

Source: Vuchic (2007, p.51) (adapted)

According to Vuchic (2007), the four most important mechanical features of vehicles are: support, guidance, propulsion, and control. These four technological elements are exclusively related to manipulating the vehicle. Table 3-17 shows ROW and technology, with their transit modes.

It is necessary to know not only physical components of the transit networks but also the characteristic indices of transit systems. Physical components can be vehicles or cars as a set travelling together, rights-of-way, stops or stations, terminals, control systems linked with electric, electronic, and communication equipment.

Transit system characteristics are: service frequency, operating speed, reliability by travel time, safety, and capacity are assessed for system performance. Further characteristics re: costs including transit fare, construction cost and operating cost, and social cost including environmental impact (Vuchic, 2007). Transit is operated with predetermined routes and transit modes halt at fixed stops or stations with a pre-set schedule of operation. Transit routes have similar features to road networks because they can be also distinguished by a series of node numbers (Edwards, 1992). “Transit networks are developed to be consistent with the appropriate highway networks and may share node and link definitions” (TRB, 2012, p.21).

Figure 3-10 shows a partial map of 3,515 routes in transit networks to be used in this study and 2,839 transit stops are shown in Figure 3-11. Characteristics of each route and stop are sourced from the 2014 Revision of Origin/Destination Data in Seoul Capital Area (Seoul Metropolitan Transportation Association, 2015).

Figure 3-8. Node Data of Road Networks (Map view)

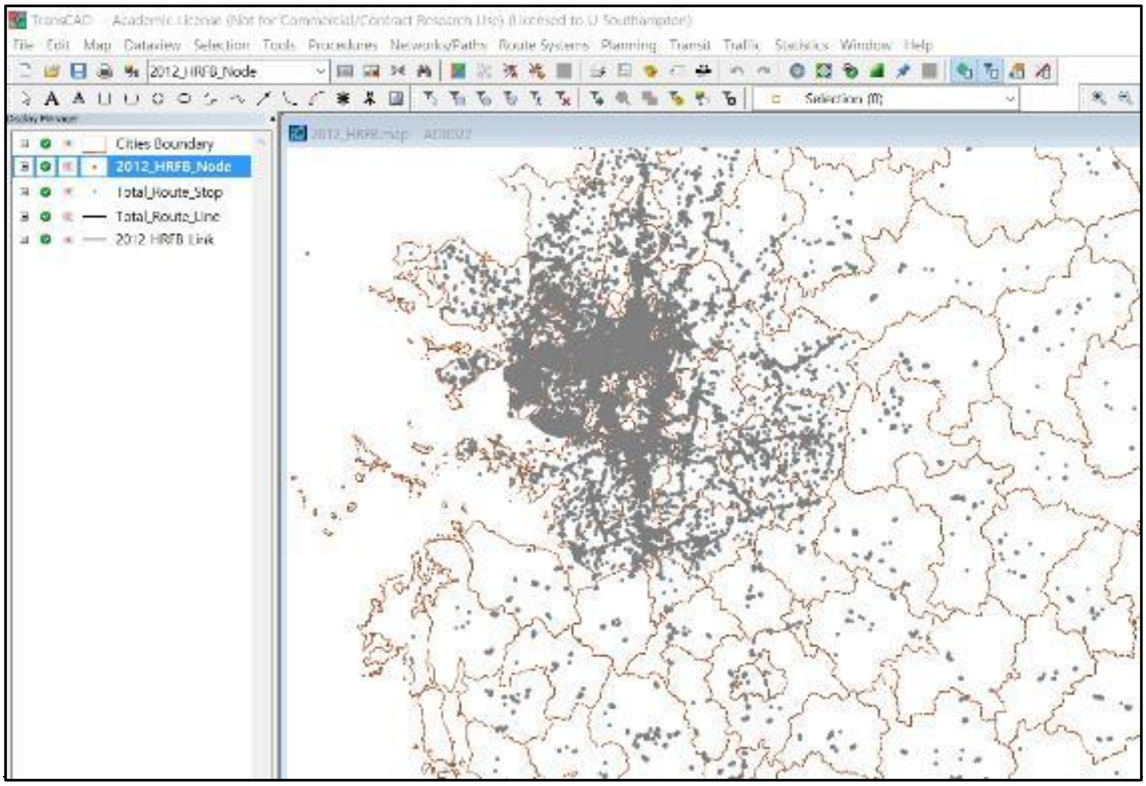


Figure 3-9.Link Data of Road Networks (Map view)

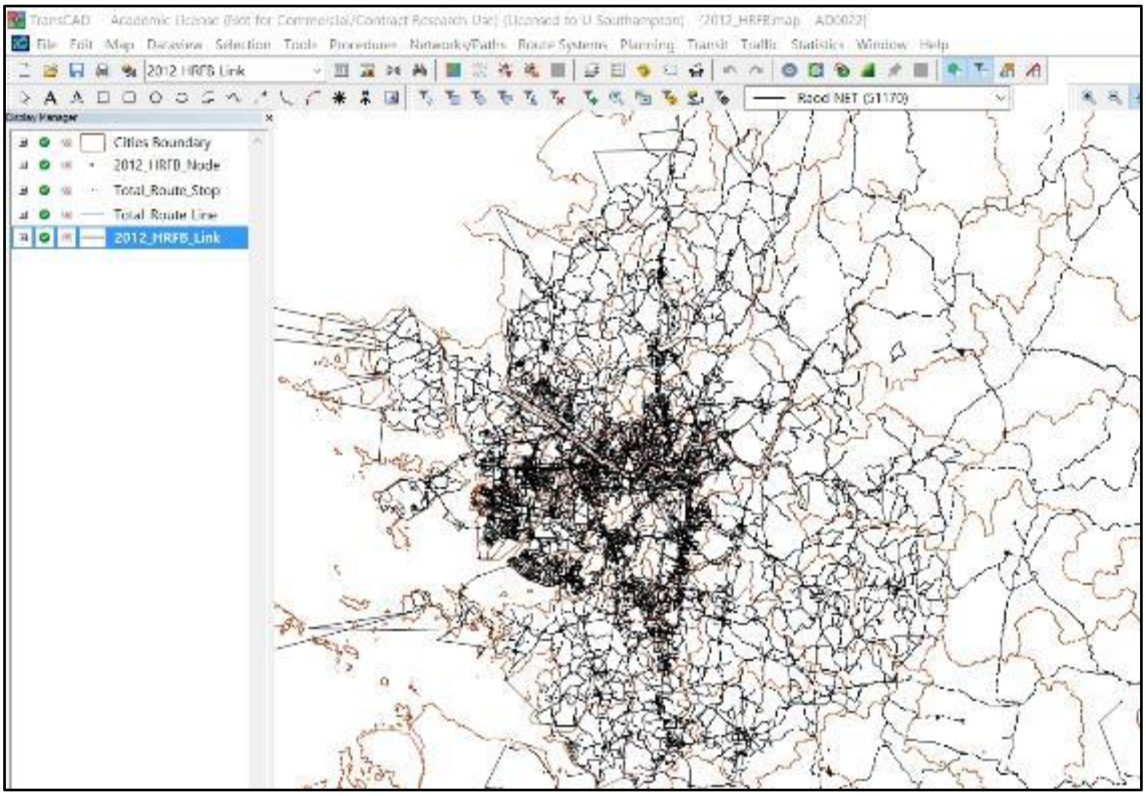


Figure 3-10. Route Data of Transit Networks (Map view)

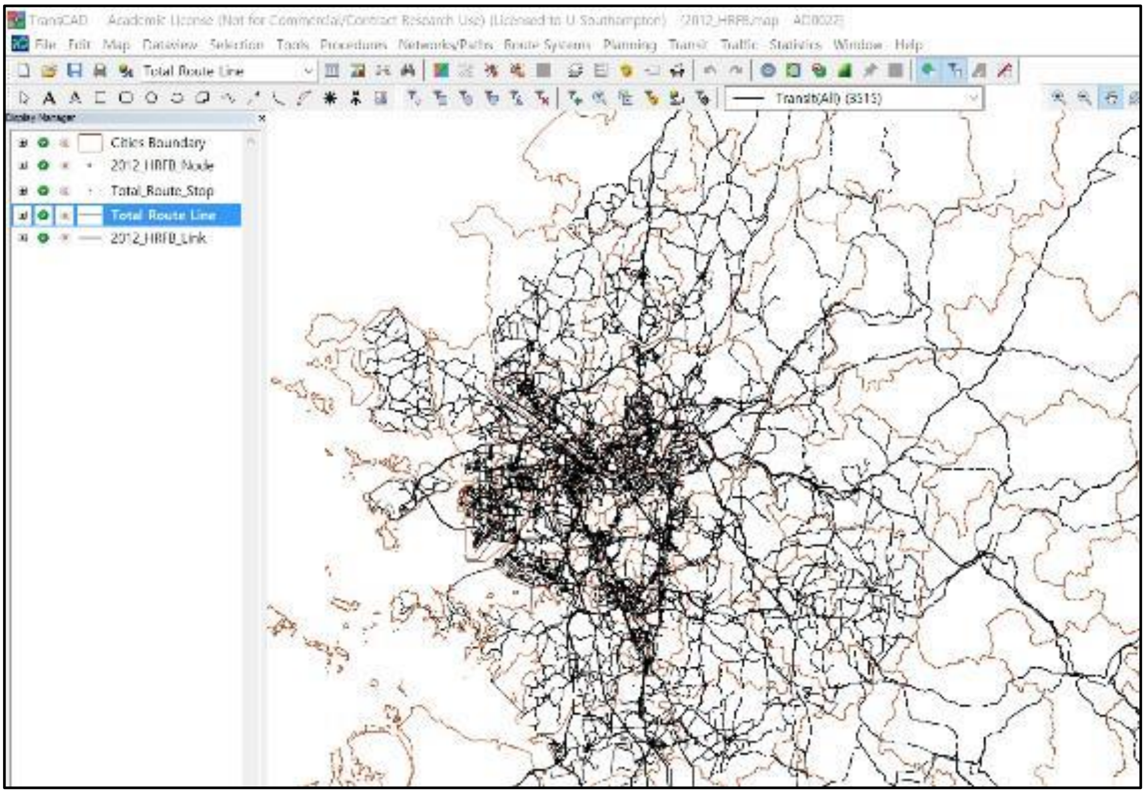
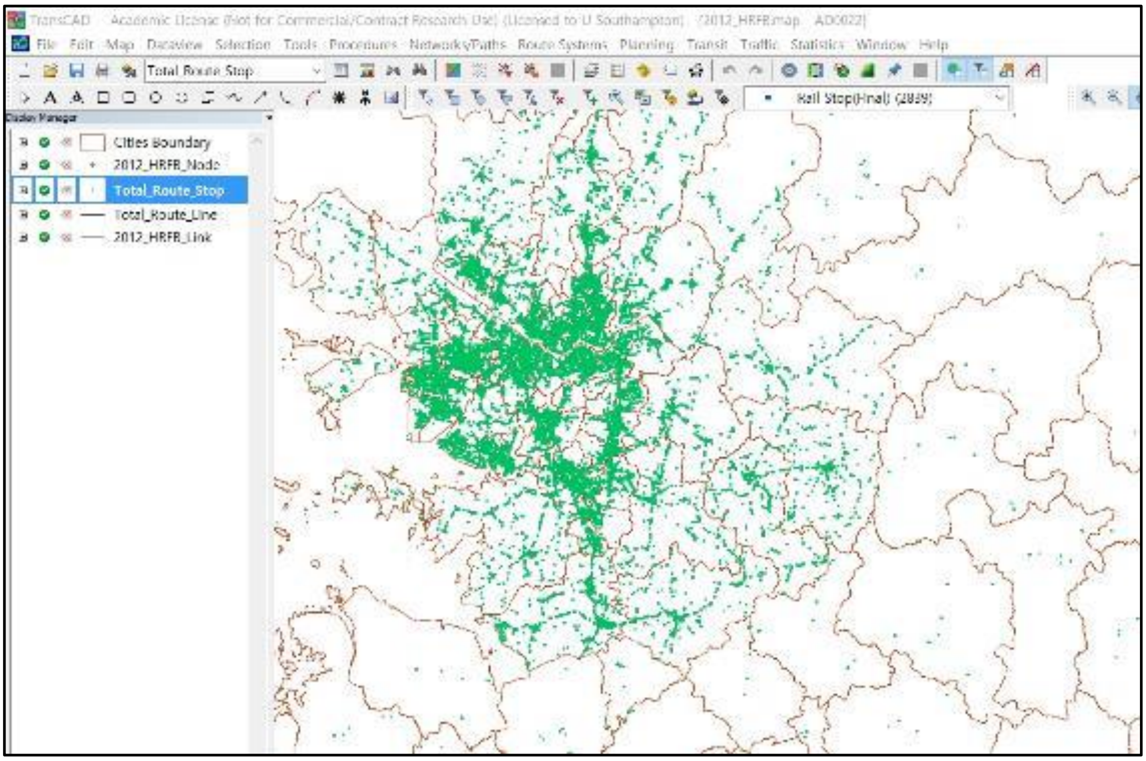


Figure 3-11. Stop Data of Transit Networks (Map view)



3.9 Summary

Chapter 3 covered the details of transport networks in the SCA in order to prepare the analysis of the normal situation of the SMRS and of the disrupted condition of the SMRS. The population of the SCA is 25.27 million (2015), comprising 49.5% of the nation's population. The importance of the SCA is revealed strongly when it comes to economic indexes. Although covering only 11.8% of the country's area, the Gross Regional Domestic Product (GRDP) of the SCA marked a half of South Korea.

The SCA has had the most developed transport infrastructure such as well-established trunk roads, highly linked subway networks, and metro bus for inter-cities. Seoul Metropolitan Railway Systems are representative facilities as public transport mode and have the widest service area among several transport modes. There are 11 operators and they are in charge of 18 separate lines. The total length of the SMRS is 1,014.4 km, having 636 stations in the whole networks.

Among various trip purposes, returning home trips amounted to 25,016,108 trips per day, comprising 42.6% of the 58,773,185 total trips. Going to work was the most frequent purpose of outbound trip from home at 19.2% of the total trips at 11,289,241. Leisure trip was the second largest outbound trip from home at 7,919,400.

For the analysis of integrated vulnerability in the SCA, the area was divided by the six transport axes: 1st Incheon axis, 2nd Suwon axis, 3rd Seongnam axis, 4th Namyangju axis, 5th Uijeongbu axis, and 6th Goyang axis. The classification criterion was the location of main subway/railway lines, considering primarily not the city population but geographically.

There have been various disruptive events on the SMRS since 1998. The causes of disruption are categorizes as four: facility problems, train problems, natural disasters, and external accidents from outside of the SMRS. Natural disasters required the longest time to be recovered from the disruptions

The SCA is minutely divided up with 1,107 traffic zones, and outside the SCA is roughly split into 130 traffic zones. In other words, there are 1,237 origins and 1,237 destinations for transport networks analysis by TransCAD. Specifically, road networks have 36,524 nodes and 51,170 links. In the transit networks, there are 3,515 routes and 2,839 transit stops in the SCA.

Chapter 4 Research Methodology

The main objective of this study is to assess the integrated vulnerability of transport networks in the SCA. What is the integrated vulnerability of transport networks? How can it be quantified? In this chapter the concept of the integrated vulnerability will be introduced by adopting the approach of total social travel costs. The process follows five stages: setting up and data collection of transport networks in the SCA; stated intention survey on the disruptions of subway network; analysis of transport networks; integrated vulnerability assessment in the SCA; and management strategies to increase the resilience of transport networks in the SCA. Several assumptions for the process are proposed, including those for transport modes transfer, information on disruptive events, and additional social travel costs.

4.1 Concept of Integrated Vulnerability of Transport Networks

To integrate means combining two or more things so that they work together. On land-based transport networks, road networks and transit networks are closely connected and they work successfully when there is an adequate modal split corresponding to the socio-economic environment. When events disrupt specific transport networks, the remaining networks may be greatly influenced by the changed O/D matrix.

Much previous research on vulnerability assessment has studied a single network only. Some studies focused on vulnerability of subway networks from the viewpoint of their topology. Other research has addressed highway networks with the cutting off of a bridge or tunnel. But a combined approach has rarely been reported (Grubesic *et al.*, 2008; Murray *et al.*, 2008; Murray, 2013; Faturechi and Miller-Hooks, 2014; Mattsson and Jenelius, 2015).

The definition used here for integrated vulnerability assessment of transport networks is a summation of a disruption's impact on both transit networks and road networks. Disruptive events can happen on transit networks and affect road networks, and the reverse can take place. When events disrupt the SMRS, people who intended to use it have to seek alternative transport modes and probably move onto the road networks. People can also use other SMRS lines that are still available. These transitions cause additional social travel costs because of congestion, waiting, or making a detour. This work adopts the total social travel costs as the summation of various kinds of travel costs that might be incurred during disruptive events.

It was assumed that a specific disruption to the SMRS happened and it affects road networks according to the changed O/D matrix. Considering the interactive impact of the SMRS and road networks, total social travel costs (TSTC) in both normal situations and extraordinary conditions will be identified as an index of the integrated vulnerability of transport networks in the SCA.

4.2 Analysis Procedure

4.2.1 Set up and Data Collection of Transport Networks in the SCA

When a disruptive event occurs on the SMRS, the changed travel time depends on the location of the station, the number of passengers who use that station, and the time of the disruptive event. A model must first be set up of the transport networks and data collection. Specific scenarios will be adopted that assume crucial sections of the SMRS for each transport axis have malfunctioned, so that travelling by the normal shortest way is no longer possible. For example, the section between Oido Station and Sadang Station of the SMRS Line 4 may be regarded as an unavailable segment because a disruptive incident happens to hinder travelling from Suwon or Anyang into Seoul. Similar scenarios will be analysed for their variation of travel time for every transport axis around Seoul. This analysis will use TransCAD to calculate travel time on the SMRS and access/transfer/egress time related to SMRS in each scenario.

4.2.2 Stated Intention Survey on Disruptions to the Subway Network

Users of public transport, who may incur several problems in the event of disruptions, have been more or less ignored when academics have defined the vulnerability of transport networks. From the viewpoint of these users, an important matter is how they can complete their original trip, even though there may be delays or additional costs due to disruptive incidents on the networks. It is also true that structural characteristics of transport networks cannot be overlooked. However, the passenger’s standpoint has to be taken into account as a fundamental variable in assessing the vulnerability when disruptive events happen.

This work identifies the influence of an individual’s intention with vulnerability assessment. In normal circumstances, commuters choose their major mode or route to go to work according to their socio-economic characteristics: distance from home to work, their income, availability of cars, accessibility of public transport services, and so on. This data can be acquired by an O/D survey (Seoul Metropolitan Transportation Association, 2015). However, since existing O/D surveys have not addressed the impact of disruptive events on the transport networks, it is difficult to understand their vulnerability using current O/D data. It is therefore necessary to undertake a stated intention survey in order to find out travellers’ reactions to disruptive events.

Stated Preference (SP) methods require a purpose-designed survey for their collection of data. SP methods consist of the use of hypothetical choice scenarios in order to lead individuals to express their preferences (Polak and Jones, 1997). Kroes and Sheldon (1988) elaborated the pros and cons of SP clearly. It is easier to control the respondents in the SP method since the researcher defines the conditions. Diverse variables, not appeared frequently using the revealed preference (RP) method, are available in the SP approach. Also, SP is cheaper to apply because it can be done online with multiple observations. People may not necessarily do in the real situation what they say they will due to non-commitment bias or policy response bias. Kroes and Sheldon (1988) asserted that the combination of SP with RP can be a good alternative to solve this major problem of stated intention/revealed behaviour. Typically, "stated preference methods are used initially to estimate the trade-off ratios in the utility function, and then aggregate revealed preference data (for example, overall levels and shares) are used to scale the utility function and obtain a model which is consistent with the revealed preference data" (Kroes and Sheldon, 1988, p.13).

The main question centres on commuters' mode choice and route selection when they are exposed to malfunctions of their normal commuting mode and route. Commuters' choice during disruptive events may change according to how long they last (KOTI, 2014). The survey will include a question about when that happens and respondents change their alternative modes. Another important question is about effective ways for system managers to deliver disruptive information to commuters. Through this question, peoples' inclination to social media or web-based service will be considered as a tool of management strategy. Commuters' individual and socio-economic characteristics are basic questions to understand the background of their choices. The group of respondents will have to be drawn from all transport axes around Seoul. This will be done by the online survey. Data collected will be analysed using a statistical program R or Excel. Considering the online survey questions and depth of their analysis, it is appropriate to adopt stated intentions rather than SP in this work (Couture and Dooley, 1981).

RP data of disruptive events in the past (e.g. the electricity cuts on the 30/3/2014) could be collected to compare with the stated intention in the specific transport axes. However, it is impossible to get RP data from commuters on all six transport axes since some have not experienced an incident. Therefore, the stated intention survey must to analyse vulnerability along all six transport axes. Of course, the current data of commuters' selection may be referred to in order to narrow the gap between (RP) and stated intention.

Current employment status will be identified corresponding to the 25 autonomous districts in Seoul Capital City. Since self-employed people have a tendency to live within a short commuting distance, this study will focus on company employees or public servants who have a long commuting distance from satellite cities around the SCA into Seoul Capital City. Response questionnaires will be classified by their transport axes by origin/destination.

4.2.3 Transport Networks Analysis in both Road Networks and the SMRS

Transport networks analysis proceeds in two stages by TransCAD: networks analysis for a normal situation of the SMRS, and a disrupted situation of the SMRS. Networks analysis for a normal situation does not require the online survey. It is just composed of road networks analysis and the SMRS analysis with the normal O/D matrix. Its main results are traffic volumes on each link of the road networks, speed of each link of road networks, number of passengers on each route of the SMRS, and travel time of each route of the SMRS.

However, for the disrupted situation, the result of the online survey is required to revise the O/D matrix. The main result of the stated intentions survey is commuters' decisions about what actions they will take to get to work when there is a disruptive event on their preferred line of the SMRS. After quantifying interrupted commuting demand, commuters will be 'redistributed' to the available transport networks except the disrupted subway line. They can detour with other subway lines or they can transfer to the bus. Cars may be preferred as an alternative. These processes are caused by the disruption of a specific subway station or line.

The first step in the analysis of the disrupted situation is to update the O/D matrix to identify by transport axis the volume/capacity ratio and increased travel time for travellers in the neighbouring road networks. Updating the O/D matrix is executed by different alternative mode shares across the six transport axes because alternative mode shares vary with axis. After that, follows road networks analysis and analysis of the SMRS, to identify the major factors such as changed travel time and traffic volume. These major variables are applied to the vulnerability assessment.

Of these analyses, the traffic assignment procedure is the complicated one and TransCAD adopts the Frank-Wolfe (FW) algorithm, based on an iterative method, to acquire the user equilibrium solution during traffic assignment, Frank and Wolfe (1956). Patriksson (2015) developed a systematic way of looking at the many algorithms that could be used to solve user equilibrium mathematically, and found that FW was the most commonly used one.

TransCAD adopts the n-conjugate user equilibrium (or n-conjugate descent FW) method, originally proposed by Daneva and Lindberg (2003), later described by Mitradjieva and Lindberg (2013). n-conjugate user equilibrium method is an advanced algorithm that quickly approaches the user equilibrium solution, but the main structure of algorithm is the same as the FW algorithm, which is elaborated in section 4.3.2.

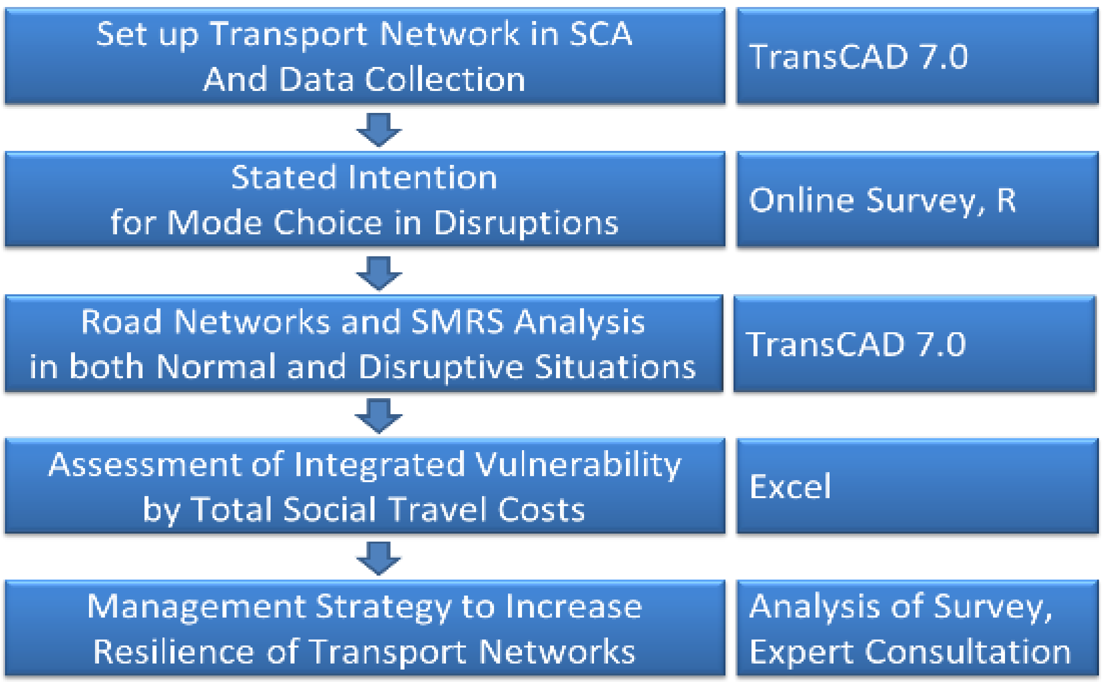
4.2.4 Integrated Vulnerability Assessment in the SCA

Integrated vulnerability of the transport networks is assessed from the perspective of total social travel costs (TSTC) composed of travel times costs, operating costs, road traffic accident costs, and environmental impact costs, which are mainly determined by the traffic volumes, speed of links, and length of links. Exact relationships were contained as several equations, which follow the guideline for the feasibility study of transport facilities in Korea. Traffic volumes and speed of links in both the normal situation and the disrupted situation are used as input to calculate the difference between two different situations. Values of TSTC for each transport axis will determine an order of vulnerability of the six axes.

4.2.5 Management Strategy to Increase Resilience of Transport Networks

To establish management strategies for the purpose of increasing resilience of the transport networks in the SCA and proposing instructions for the users in a disrupted situation, the first step is to analyse the vulnerability of each transport axis and the intention survey of commuters. Next, expert consultation will be organised so that an effective management strategy for the emergency environment can be drawn up. Those working in various fields of transportation operation, disaster prevention, mass media, social media, and central/local government will be contacted to produce substantial management strategy. In particular, it is essential to consult the Ministry of Public Safety and Security in Korea, which is in charge of delivering urgent messages in disaster situations.

Figure 4-1. Research Methodology Procedure



4.3 Process of TransCAD Analysis

TransCAD is a macro simulation program for transport planning, based on a classic four-stage transport planning model. The process of TransCAD analysis comprises the six steps shown in Figure 4-2.

Figure 4-2. TransCAD analysis Process

1. Data Collection	Basic Map, Origin/Destination data, Zones, Links/Nodes, Value of travel time for each modes
2. Creation of Road Networks	Setting of Inputs, Lookup table, Turn prohibition table, Networks fields
3. Trip Assignment on Road Networks	Multi-Modal Multi-Class Assignment - Basic map, O/D data, Road networks - Setting of Networks, OD class matrices, Delay function parameters, Iterations/Relative gap
4. Creation of SMRS Networks	Setting of Inputs, Link fields, Route fields, Stop fields, Node fields, Non-Transit
5. Trip Assignment on SMRS Networks	Equilibrium Pathfinder Assignment - Basic map, O/D data, SMRS networks - Setting of Networks (general, mode, fare, times, etc.), OD fields, Parameters, Iterations/Convergence
6. Summary of Analysis Result	Data view of Link Flows in Road Networks Data view of Transit Flows

4.3.1 Data Collection for TransCAD

The elementary data for TransCAD analysis are the basic map, origin/destination, traffic zones, links/nodes for road networks, routes/stops for the SMRS, and value of travel times for each transport mode. The basic map is a fundamental frame that is used in TransCAD to link geographical characteristics and topological position with quantitative information. Details of the others are elaborated in Chapter 6.

4.3.2 Creation of Road Networks and Trip Assignment

O/D data for each transport mode means that trip production, trip distribution and mode choices are already executed. This research adopts six transport modes: car, bus with scheduled operation, another bus, taxi, truck, the SMRS, including transfer between the SMRS and bus. The O/D data in the normal situation are from the 2014 Revision of Origin/Destination Data in Seoul Capital Area (Seoul Metropolitan Transportation Association, 2015).

In the process of trip assignment, the volume dependence of travel times is mainly used, resulting in the calculation of link flows and travel times that are mutually consistent. Despite iteration between assigning flows and calculating loaded travel times, which causes additional computational burden, the equilibrium method is one of the best approaches to assignment. Traffic assignment is the aggregation for each traveller. It is assumed that all travellers have perfect information about network alternatives and they choose routes to minimise their travel time or travel costs (Caliper, 2015). This is known as Wardrop's first principle or user equilibrium, which assumes that paths are chosen so that no trip-maker individually can obtain an advantage by changing path (Wardrop, 1952).

TransCAD uses the FW algorithm to solve user equilibrium problem, utilising an iterative process to achieve convergence. TransCAD computes network link flows based upon flow-dependent travel times in each iteration. Since the FW algorithm was first suggested, researchers have identified methods that converge more rapidly. However, the slow convergence of FW is a well-known problem and a number of improvements have been suggested to speed up convergence (see the studies of Weintraub *et al.* (1985) and Bell and Iida (1997)).

Alternative methods offer better convergence properties, especially for large and congested networks. n-conjugate user equilibrium method is used in TransCAD for the process of trip assignment (Caliper, 2015). These methods are aiming to find a better $\emptyset$ to converge more quickly toward the optimum situation. Despite several advanced algorithms, the FW algorithm has been the fundamental one to understand the iterative solution to get the user equilibrium status in the trip assignment process (see Table 4-1).

Table 4-1. Frank-Wolfe Algorithm

Step 1.	Select a suitable initial set of current link costs, usually free-flow travel time $C_a(0)$. Initialise all flows $V_a^0 = 0$; make n = 0.
Step 2.	Build the set of minimum cost trees with the current costs; make n = n + 1.

Step 3.	Load the whole trip matrix **T** by all-or-nothing assignment on the basis of cost trees from step 2, obtaining a set of auxiliary flows V_a^{AON}.
Step 4.	Calculate the current flows as: $V_a^n = (1-\emptyset)V_a^{n-1} + \emptyset V_a^{AON}$, choosing $\emptyset$ such that the value of the objective function Z is minimised, $(0 \leq \emptyset \leq 1)$.
Step 5.	Calculate a new set of current link costs based on the flows V_a^n; use a good convergence indicator (say Relative Gap < 0.0001) to decide whether to stop or to proceed to Step 2.

Source: de Dios Ortúzar and Willumsen (2011, p.398)

User equilibrium flows cannot be calculated directly but are estimated with the iterative FW algorithm., The quality of the solution therefore depends on the level of convergence of the algorithm. In other words, it is important to choose a well-designed criterion of convergence. At equilibrium, the difference between the current flow loading and the shortest path loading, known as the duality gap, has a zero value. TransCAD uses a measure called the relative gap (R.G.) as the stopping criterion for the traditional user equilibrium assignment (Caliper, 2015).

Rose *et al.* (1988) studied a variety of convergence criteria and looked into their usefulness for ascertaining proximity to the correct solution. They recommended the R.G. as the most reliable measure of convergence, Equation 4-1:

$$R.G. = \frac{\sum_a (V_a^* \times C_a) - \sum_a (V_a^{AON} \times C_a)}{\sum_a (V_a^* \times C_a)} \tag{4-1}$$

where

V_a^* : current flow on link *a*

V_a^{AON} : All or nothing flow on link *a*

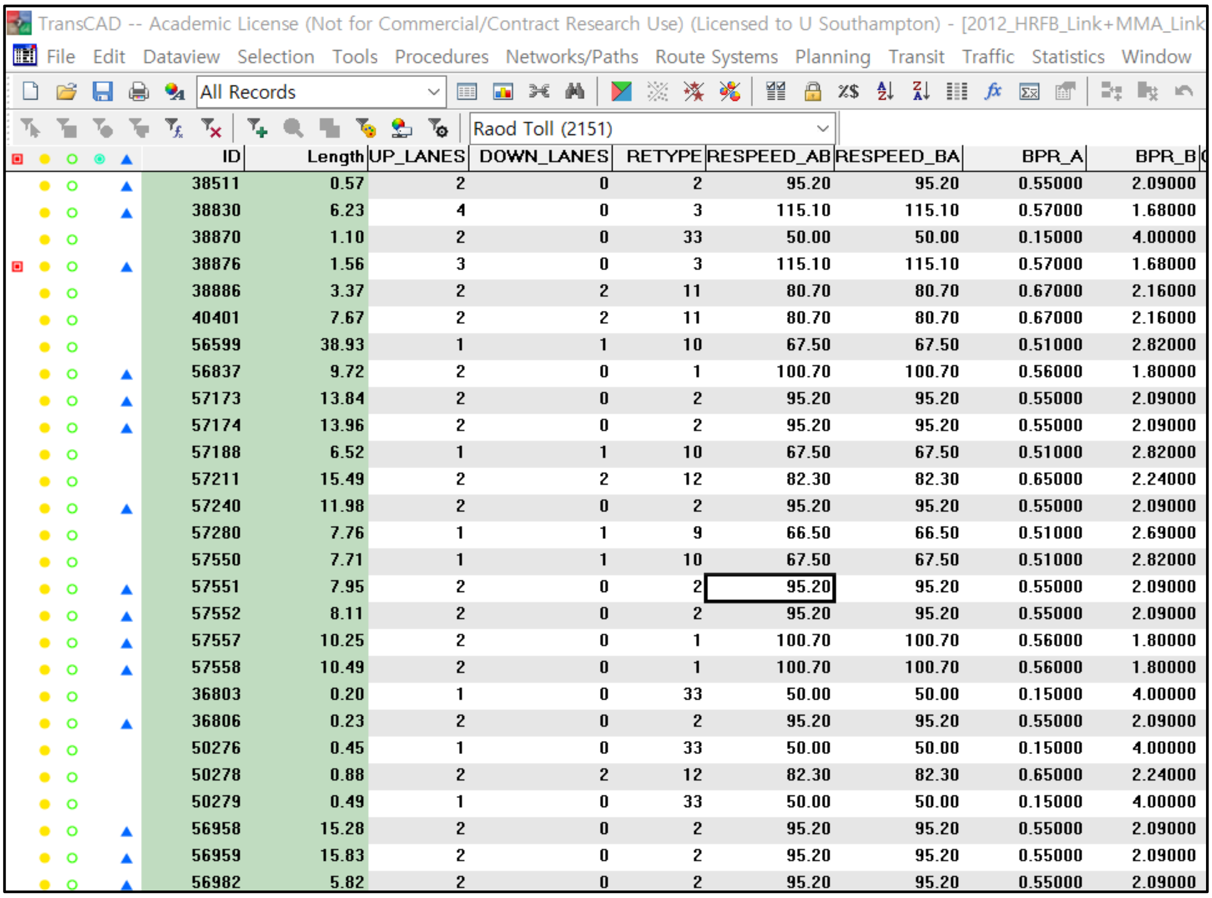
C_a : cost at the current flow on link *a*

The R.G. would be zero at true equilibrium because the R.G. is the estimated difference between the current solution and the optimal equilibrium solution. The all-or-nothing solution can be seen as a lower bound for the traffic assignment problem. A number of tests have been proposed to determine how close is close enough, for transport networks analysis. This would depend on the relative size of the user benefits that are being estimated. Boyce *et al.* (2004) investigated this issue in some practical cases and recommended that the R.G. should be at most 0.1% (0.0001) for satisfactory convergence.

There are in fact, several traffic assignment methods available in TransCAD: single-class traffic assignment, multi-modal multi-class assignment (MMA), traffic assignment with volume dependent turning delays, macroscopic dynamic traffic assignment, and transit assignment. All of these algorithms are based on the FW algorithm. This study used MMA for trip assignment of road networks. MMA is based on a user equilibrium method and is suitable for modelling HOV (high occupancy vehicle) lanes, toll roads, and various types of vehicle such as cars, trucks of different sizes, and buses. In order to assign trips on the road networks, road networks have to be created by setting up inputs, lookup table, turn prohibition table, and network fields. Creating road networks is the process of setting up the environment for transport demands to be assigned to specific links with particular transport modes.

Detailed settings for traffic assignment are as follows. Transport modes consist of cars, buses with scheduled operations, other buses like chartered buses, taxis, trucks, and the SMRS. The BPR function is used for volume-delay relationship. Parameter *alpha* is 0.15 and parameter *beta* is 4 for BPR function. The number of iteration was set at 500 and the relative gap of travel times among links was constrained to 10^{-7}. Figure 4-3 and Figure 4-4 should be read alongside one another and show part of the result of trip assignment on road networks in the normal situation.

Figure 4-3. Result of Trip Assignment on Road Networks in Normal Situation – Part 1



ID	Length	UP_LANES	DOWN_LANES	RETYPE	RESPEED_AB	RESPEED_BA	BPR_A	BPR_B
38511	0.57	2	0	2	95.20	95.20	0.55000	2.09000
38830	6.23	4	0	3	115.10	115.10	0.57000	1.68000
38870	1.10	2	0	33	50.00	50.00	0.15000	4.00000
38876	1.56	3	0	3	115.10	115.10	0.57000	1.68000
38886	3.37	2	2	11	80.70	80.70	0.67000	2.16000
40401	7.67	2	2	11	80.70	80.70	0.67000	2.16000
56599	38.93	1	1	10	67.50	67.50	0.51000	2.82000
56837	9.72	2	0	1	100.70	100.70	0.56000	1.80000
57173	13.84	2	0	2	95.20	95.20	0.55000	2.09000
57174	13.96	2	0	2	95.20	95.20	0.55000	2.09000
57188	6.52	1	1	10	67.50	67.50	0.51000	2.82000
57211	15.49	2	2	12	82.30	82.30	0.65000	2.24000
57240	11.98	2	0	2	95.20	95.20	0.55000	2.09000
57280	7.76	1	1	9	66.50	66.50	0.51000	2.69000
57550	7.71	1	1	10	67.50	67.50	0.51000	2.82000
57551	7.95	2	0	2	95.20	95.20	0.55000	2.09000
57552	8.11	2	0	2	95.20	95.20	0.55000	2.09000
57557	10.25	2	0	1	100.70	100.70	0.56000	1.80000
57558	10.49	2	0	1	100.70	100.70	0.56000	1.80000
36803	0.20	1	0	33	50.00	50.00	0.15000	4.00000
36806	0.23	2	0	2	95.20	95.20	0.55000	2.09000
50276	0.45	1	0	33	50.00	50.00	0.15000	4.00000
50278	0.88	2	2	12	82.30	82.30	0.65000	2.24000
50279	0.49	1	0	33	50.00	50.00	0.15000	4.00000
56958	15.28	2	0	2	95.20	95.20	0.55000	2.09000
56959	15.83	2	0	2	95.20	95.20	0.55000	2.09000
56982	5.82	2	0	2	95.20	95.20	0.55000	2.09000

ID: link ID, Length: length of link (km); UP_LANES: lane numbers in up direction (or AB direction)
DOWN_LANES: lane numbers in down direction (or BA direction);
RESPEED_AB(BA): design speed of AB(BA) direction of the lane (km/h)
BPR_A: parameter A of the BPR VDR; BPR_B: parameter B of the BPR VDR.

Figure 4-4. Result of Trip Assignment on Road Networks in Normal Situation – Part 2

kFlows+Wa - Result (2015).dvw - 2]
Help

CAPA_day_AB	CAPA_day_BA	A_Time_day_AB	A_Time_day_BA	TOLL	AB_Flow_PCE	BA_Flow_PCE	Tot_Flow_PCE
35720	35720	0.4200	0.4200	3	19736.9392	—	19736.9392
81120	81120	4.5778	4.5778	3	66599.9116	—	66599.9116
20000	20000	2.1740	2.1740	3	28766.8451	—	28766.8451
60840	60840	0.9886	0.9886	3	34388.9213	—	34388.9213
28400	28400	3.5610	3.3793	0	22866.4044	20945.6413	43812.0458
28400	28400	5.7046	5.7046	0	23.0940	9.0406	32.1346
10900	10900	34.6050	34.6050	0	0.0000	0.0000	0.0000
36920	36920	5.7927	5.7927	3	230.5514	—	230.5514
35720	35720	9.9519	9.9519	3	18624.4510	—	18624.4510
35720	35720	9.6384	9.6384	3	15468.0310	—	15468.0310
10900	10900	5.7962	5.7962	0	19.3060	23.8021	43.1081
28000	28000	11.3005	11.3022	0	1509.9795	1610.5616	3120.5412
35720	35720	8.7296	8.7296	3	19532.4283	—	19532.4283
8000	8000	7.0022	7.0029	0	4.1420	336.1216	340.2636
10900	10900	6.8549	6.8549	0	0.0000	0.0000	0.0000
35720	35720	5.0685	5.0685	3	5479.3892	—	5479.3892
35720	35720	5.2376	5.2376	3	8082.7527	—	8082.7527
36920	36920	6.6630	6.6630	3	13483.1732	—	13483.1732
36920	36920	7.1268	7.1268	3	17112.8519	—	17112.8519
10000	10000	0.2442	0.2442	3	0.0000	—	0.0000
35720	35720	0.1494	0.1494	3	6949.8583	—	6949.8583
10000	10000	0.5453	0.5453	0	0.0000	—	0.0000
28000	28000	0.6423	0.6423	0	158.6170	173.3160	331.9330
10000	10000	0.5901	0.5901	0	0.0000	—	0.0000
35720	35720	9.8201	9.8201	3	7312.3223	—	7312.3223
35720	35720	10.2554	10.2554	3	8576.2351	—	8576.2351
35720	35720	3.7114	3.7114	3	5689.4635	—	5689.4635
35720	35720	4.8178	4.8178	3	2685.9840	—	2685.9840
35720	35720	4.8484	4.8484	3	2946.0124	—	2946.0124

CAPA_day_AB(BA): daily capacity of AB(BA) direction of the lane
A_Time_Day_AB(BA): daily average travel time of AB(BA) direction of the lane
AB(BA)_Flow_PCE: passenger car equivalent (PCE) flow of AB(BA) direction of the lane
Tot_Flow_PCE: passenger car equivalent (PCE) flow of both directions of the lane

4.3.3 Creation of the SMRS Networks and Trip Assignment

Creating the SMRS networks means defining routes, stops, and non-transit attributes of the networks in order to assign passengers within the SMRS. Non-transit attributes are related to accessing, transferring, and egressing to the SRMS by walking or other transport modes. Creating the SMRS networks is also an essential step before trip assignment. TransCAD supplies several methods for transit trip assignment: all or nothing method, pathfinder, stochastic user equilibrium, equilibrium pathfinder, and schedule-based user equilibrium.

As its name suggests, in the All or nothing method all travellers for an origin/destination pair are assigned to the single best transit path connecting them. This method assumes that there is no capacity limit and all travellers perceive and weigh the same attributes for route choice in the same way. “Naive all or nothing approaches would only be acceptable for sparse and long distance travel networks” (de Dios Ortúzar and Willumsen, 2011, p.377).

The Pathfinder method is a generalisation of and improvement on the optimal strategies method. The optimal strategies method assumes that travellers behave in a way to minimise their total expected travel time, which is the weighted sum of expected walk, wait, and in-vehicle time. However, the distinctive characteristic of the pathfinder method is considering fares in order to determine the best transit route, compared with the optimal strategies method. The generalised cost of travel, including total travel time and fare, is a determinant to be minimised in the pathfinding process. Specifically, the generalised cost of travel is computed by applying a value of travel time (VOT), which is user-specified, to convert travel and wait times to monetary units, which are then combined with the applicable fares (Spiess and Florian, 1989; Caliper, 2015).

The Stochastic User Equilibrium (SUE) method is a generalisation of user equilibrium. SUE assumes that travellers do not have perfect information and perceive travel costs in different ways, although all travellers have recognised the occurrence of a disruptive event. Since SUE assignment permits use of less attractive routes as well as the most attractive ones, it seems that they might generate more feasible outcomes than the deterministic User Equilibrium model. Under SUE transit assignment, travellers select paths from their origin to their destination, considering the overall attractiveness of each path, computed from the travel time components, transfer penalties, and fares. On the first iteration, flow is allocated to the shortest path and the generalised cost on the network is updated based upon the flows. On the second iteration the process is repeated, and a different path is typically obtained. At the end of the final allocation of flow, no traveller can increase their expected utility by changing paths and the stochastic user equilibrium is reached. SUE assignment has a particular advantage for predicting route utilisation when there are many alternatives for transit paths with no capacity issues. It does not take into account capacity constraints to the same extent as other algorithms and this is a major weakness in instances of service disruption (de Dios Ortúzar and Willumsen, 2011; Caliper, 2015).

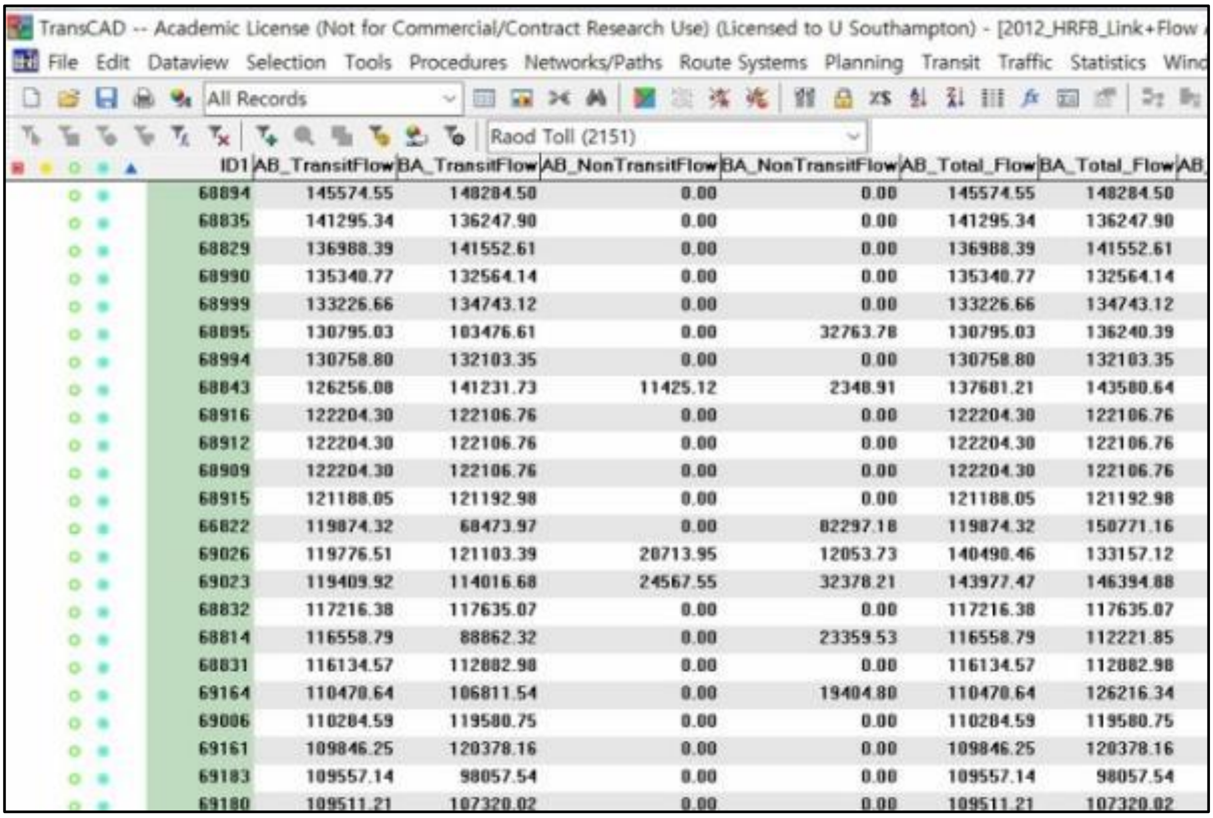
The Equilibrium Pathfinder assignment method is an extended version of the Pathfinder method that reflects capacities of route, parking, and non-transit links. There are access links, egress links, transfer links, and station access links for non-transit links. Travel costs are calculated by the ratio of volume to capacity and the delay function of routes. The higher costs of the previous iteration are input into the next iteration, and new path allocations are performed leading to a new set of values. Volumes are updated by using the successive averages of the current and previous flows. After a sufficient number of iterations, the differences in results decreases until it reaches convergence. This method assumes that passengers will take the first transit line within its capacity which will get them to their destination in a reasonable amount of time. Different paths are utilised based on service times, frequencies and capacities. Therefore, it is not necessary that all passengers know all attributes of transit routes (Caliper, 2015).

One of the strengths of the Equilibrium Pathfinder method is a multi-class transit assignment in which multiple classes of users are assigned simultaneously. There are different classes of public transit users: classes by mode like bus riders versus subway riders, classes by access type such as walk access versus drive access, and classes by demographic group like low income versus high income. The multi-class property of the Equilibrium Pathfinder allows simultaneous and sequential assignment, which results in both saving on run times and eliminating the need for post data aggregation. Additionally, applying the capacities to each network component can make the assignment more accurate and realistic, compared to the Stochastic User Equilibrium method (Caliper, 2015).

The Schedule-Based method uses actual transit route schedules to determine wait time, transfer times, and other transit costs, so as to find the minimum-cost path between an origin and destination (Caliper, 2015).

This work uses the Equilibrium Pathfinder assignment method, which can provide a more elaborate and realistic treatment of access, egress, and transfer links and the use of fares, in the computation of the best paths. The equilibrium pathfinder method is a kind of optimal strategy method that assigns transit trips according to the probability of boarding, determined by its frequency. In detail, information of link characteristics like flows, times and costs, comes from the result of assignment of road networks. Variation of transit fare by trip route has not been considered because of the integrated public transport fare system in the SCA, which is based on not the number of transfers but the location of origin and destination. In other words, if a transit passenger has three routes from an origin to a specific destination, a total fare is almost the same regardless of their optimal choice from the perspective of travel time. Additionally, the real headway of the SMRS is taken into account in the assignment process. Figure 4-5 and Figure 4-6 should be read alongside one another and show a part of the results of the trip assignment on the SMRS networks in a normal situation.

Figure 4-5. Result of Trip Assignment on the SMRS Networks in Normal Situation – Part 1



ID1	AB_TransitFlow	BA_TransitFlow	AB_NonTransitFlow	BA_NonTransitFlow	AB_Total_Flow	BA_Total_Flow
68894	145574.55	148284.50	0.00	0.00	145574.55	148284.50
68835	141295.34	136247.90	0.00	0.00	141295.34	136247.90
68829	136988.39	141552.61	0.00	0.00	136988.39	141552.61
68990	135340.77	132564.14	0.00	0.00	135340.77	132564.14
68999	133226.66	134743.12	0.00	0.00	133226.66	134743.12
68895	130795.03	103476.61	0.00	32763.78	130795.03	136240.39
68994	130758.80	132103.35	0.00	0.00	130758.80	132103.35
68843	126256.08	141231.73	11425.12	2348.91	137681.21	143580.64
68916	122204.30	122106.76	0.00	0.00	122204.30	122106.76
68912	122204.30	122106.76	0.00	0.00	122204.30	122106.76
68909	122204.30	122106.76	0.00	0.00	122204.30	122106.76
68915	121188.05	121192.98	0.00	0.00	121188.05	121192.98
66822	119874.32	68473.97	0.00	82297.18	119874.32	150771.16
69026	119776.51	121103.39	20713.95	12053.73	140490.46	133157.12
69023	119409.92	114016.68	24567.55	32378.21	143977.47	146394.88
68832	117216.38	117635.07	0.00	0.00	117216.38	117635.07
68814	116558.79	88862.32	0.00	23359.53	116558.79	112221.85
68831	116134.57	112882.98	0.00	0.00	116134.57	112882.98
69164	110470.64	106811.54	0.00	19404.80	110470.64	126216.34
69006	110284.59	119580.75	0.00	0.00	110284.59	119580.75
69161	109846.25	120378.16	0.00	0.00	109846.25	120378.16
69183	109557.14	98057.54	0.00	0.00	109557.14	98057.54
69180	109511.21	107320.02	0.00	0.00	109511.21	107320.02

ID1: Route ID; AB(BA)_TransitFlow: in-vehicle flows (passengers) of direction AB(BA) of transit route

AB(BA)_NonTransitFlow: sum of access flows (passengers), transfer flows (passengers), and egress flows (passengers) of direction AB(BA) of transit route

AB(BA)_Total_Flow: total flows (passengers) of direction AB(BA) of transit route

Figure 4-6. Result of Trip Assignment on the SMRS Networks in Normal Situation – Part 2

ow Aggregation.dvw - 2012_HRFB_Li

Window Help

AB_Access_Walk_Flow	BA_Access_Walk_Flow	AB_Xfer_Walk_Flow	BA_Xfer_Walk_Flow	AB_Egress_Walk_Flow	BA_Egress_Walk_Flow
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	32763.78	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	2348.91	11007.61	0.00	417.51	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	82297.18	0.00	0.00
0.00	0.00	20713.95	12053.73	0.00	0.00
0.00	1271.37	22943.58	31106.84	1623.97	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	23359.53	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	19404.80	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00

AB(BA)_Access_Walk_Flow: walk flows (passengers) for access of direction AB(BA) of transit route

AB(BA)_Xfer_Walk_Flow: walk flows (passengers) for transfer of direction AB(BA) of transit route

AB(BA)_Egress_Walk_Flow: walk flows (passengers) for egress of direction AB(BA) of transit route

4.3.4 Summary of Analysis Result

The major output of the analysis is traffic flows and travel times on all the links of road networks and all the routes of SMRS networks. Multiplication of traffic flows, travel times, and average value of travel time (AVTT) for all transport modes aggregates the TSTC.

4.4 Expert Interview as a Qualitative Research Method

Expert interviews will be undertaken in order to outline management strategies for a more resilient transport network in the SCA. Management strategies are not numerical solutions that can be traced step by step, but require diverse opinions from different people.

Research method can be simply classified as qualitative and quantitative, and a mixture of course. The qualitative research method is appropriate for collecting opinions from open questions and text is used as input. The qualitative research method is more frequently applied in the humanities or social sciences than natural sciences or engineering. By contrast, quantitative research focuses on logical relationships among variables, which can be identified by numerical analysis or experiment (Creswell, 2013). One of the most frequent approaches for qualitative research method is the grounded theory, developed by the sociologists Barney Glaser and Anselm Strauss (Glaser and Strauss, 1966). Grounded theory can be defined as an inductive research method because analysing fundamental data is needed in order to suggest concepts, categories, and theories (Bernard, 2012). Basic data is represented in several forms including recording in scripts as well as written texts.

This research adopts interviews with experts as a way of acquiring three categories of management strategy for the SMRS and their detailed tactics for more resilient transport networks in the SCA. Experts will be interviewed who have been involved with the operation of the SMRS or have studied transport networks at university and in research institutes. This includes central government officials from the Ministry of Land, Infrastructure and Transport, and the Ministry of Public Safety and Security. Local government officials in charge of emergency plan for the disruptive situation of the SMRS, will be invited to participate in this research. In addition, managers from operators of the SMRS will also be invited to take part, both public and private operators. Further, professors from several universities and researchers from public research institutes will be invited to suggest significant management strategies. Most interviews will be performed face-to-face, but paper interviews will be used in addition. The questionnaire for the experts' interviews is in three sections: evaluation of current transport networks in the SCA, assessment of current measures on the disruptive events on the SMRS, and suggestions to make transport networks in the SCA more resilient when events disrupt the SMRS.

4.5 Assumptions for Analysis

The suitability of assumptions influences the reliability of outcomes in most research. Although it is impossible to model reality perfectly, rational hypotheses can produce trustworthy results. Assessing the vulnerability of transport networks must be undertaken with some assumptions because results come from an imaginary situation. This section will elaborate the assumptions for: mode transfer from the SMRS, information of disruptive events, and additional social travel cost.

4.5.1 Assumptions about Mode Transfer

The main assumption for assessing integrated vulnerability of entire transport networks is a mode transfer from the SMRS to road networks. Users of the SMRS in a disruptive situation have to choose to substitute car, taxi, bus or another line of the SMRS. Therefore, it is necessary to analyse car ownership by household and operational information of bus and taxi.

Principal assumptions regarding mode shift are:

- People who possess their own car and want to use it as a substitute for the disrupted SMRS within their transport axis have no problem in using them.
- People who want to use a taxi as a substitute for the disrupted SMRS can use one with as difficulty as normal. Additionally, those who do not possess their own car but want to travel by car, can use a taxi without any problems by pre-booking.
- There is no capacity problem in the bus service. Anyone who wants to take a bus as an alternative for non-operational SMRS can use existing scheduled buses or additionally provided chartered buses.
- No travellers give up their journey because of the disrupted SMRS.
- The response to the disrupted SMRS is the same for commuters and for travellers whose trip purposes are not going to work.

The assumption of unlimited transferring from the SMRS to cars can be rationalised with travel data by transport mode (see Table 4-2) and car ownership of households in the SCA (see Table 4-3). Table 4-2 shows that car sharing comprised 21.1% of total trips while the use of the SMRS consisted of 13.2% total trips in the SCA. Table 4-3 illustrates that average rate of car ownership of households in the SCA is 101.2% and the values of Incheon and Gyeonggi were 129.6% and 112.1% respectively.

Although there can be more than two travellers in each household, 50.4% of households in the SCA comprise one or two people, see Table 4-4. Therefore, people who want to use their own cars for the disrupted SMRS would no difficulty in using them. It is possible, in the real situation, that a specific section of road networks may get clogged because travellers are provided with traffic information imperfectly. However, in the analysis for this research, it is assumed that travellers are well-distributed according to the user equilibrium status.

Table 4-2. Car Sharing compared with the SMRS in the SCA in trips/day (2013)

						(unit: trips/day)
Mode	Desti. / Origin	Seoul	Incheon	Gyeonggi	Outside of SCA	Subtotal
Auto	Seoul	5,699,588	2,854	31,861	0	5,734,303
	Incheon	2,920	1,455,481	5,939	0	1,464,340
	Gyeonggi	27,521	6,013	6,491,828	3,199	6,528,561
	Outside of SCA	0	0	2,190	0	2,190
	Subtotal	5,730,028	1,464,348	6,531,819	3,199	13,729,393
	Ratio	-	-	-	-	21.1%
SMRS	Desti. / Origin	Seoul	Incheon	Gyeonggi	Outside of SCA	Subtotal
	Seoul	5,415,896	154,275	787,930	10,787	6,368,888
	Incheon	167,373	251,123	82,523	565	501,583
	Gyeonggi	818,747	80,943	722,219	35,613	1,657,522
	Outside of SCA	9,062	720	22,814	0	32,596
	Subtotal	6,411,077	487,061	1,615,486	46,964	8,560,588
	Ratio	-	-	-	-	13.2%
Total	Desti. / Origin	Seoul	Incheon	Gyeonggi	Outside of SCA	Subtotal
	Seoul	25,733,054	436,129	3,257,212	328,348	29,754,743
	Incheon	439,822	5,487,970	599,104	56,534	6,583,430
	Gyeonggi	3,134,443	539,276	23,730,343	392,563	27,796,625
	Outside of SCA	327,238	72,538	399,725	0	799,502
	Subtotal	29,634,557	6,535,914	27,986,384	777,445	64,934,299
	Ratio	-	-	-	-	100.0%

Source: 2014 Revision of Origin/Destination Data in the Seoul Capital Area (adapted)

Table 4-3. Car Ownership of Households in the SCA (2015)

Transport Axis	Population	Household	Autos	Autos/Household
1. Incheon	4,086,928	1,465,171	1,790,017	122.2%
2. Suwon	4,618,200	1,606,518	1,778,275	110.7%
3. Seongnam	2,230,362	787,673	869,381	110.4%
4. Namyangju	1,065,892	373,927	422,359	113.0%
5. Uijeongbu	888,379	317,817	345,541	108.7%
6. Goyang	1,405,418	494,142	548,187	110.9%
SCA	**25,273,824**	**9,214,649**	**9,328,886**	**101.2%**
Seoul	9,904,312	3,784,490	3,056,588	80.8%
Incheon	2,890,451	1,045,417	1,355,207	129.6%
Gyeonggi	12,479,061	4,384,742	4,917,091	112.1%
Nationwide	**51,069,375**	**19,111,030**	**20,989,885**	**109.8%**

Source: Korean Statistical Information Service, http://kosis.kr (adapted, 2017)

Table 4-4. Classification of Households by Number of Members (2015)

Region	No. of Household Member						
	Whole	one	two	three	four	five	six or over
Nationwide	19,111,030	5,203,440	4,993,818	4,100,979	3,588,931	940,413	283,449
ratio	100.0%	27.2%	26.1%	21.5%	18.8%	4.9%	1.5%
SCA	9,214,649	2,385,893	2,257,768	2,067,905	1,893,629	471,304	138,150
ratio	100.0%	25.9%	24.5%	22.4%	20.6%	5.1%	1.5%
Seoul	3,784,490	1,115,744	930,467	817,440	701,945	169,436	49,458
ratio	100.0%	29.5%	24.6%	21.6%	18.5%	4.5%	1.3%
Incheon	1,045,417	243,678	265,079	245,135	220,538	55,230	15,757
ratio	100.0%	23.3%	25.4%	23.4%	21.1%	5.3%	1.5%
Gyeonggi	4,384,742	1,026,471	1,062,222	1,005,330	971,146	246,638	72,935
ratio	100.0%	23.4%	24.2%	22.9%	22.1%	5.6%	1.7%

Source: Korean Statistical Information Service, http://kosis.kr (adapted, 2017)

The capacity problem of taxis or buses can be discussed using the data in Table 4-5. The principal legal foundation for taxi and bus services in Korea is the Passenger Transport Service Act[4].

Table 4-5. Number of Buses and Taxis in the SCA (2015)

Car No. / Region	Intracity Bus	Intercity Bus	Chartered Bus	Corporate Taxi	Privately-Owned Taxi
Nationwide	33,765	7,754	45,670	89,933	164,617
SCA	20,436	1,947	20,089	38,643	84,716
Seoul	7,482	0	3,910	22,760	49,336
Incheon	2,285	0	2,201	5,385	9,008
Gyeonggi	10,669	1,947	13,978	10,498	26,372

Source: MOLIT Statistics System, http://stat.molit.go.kr (adapted, 2017)

Taxis are divided into corporate taxis and personal taxis. The distinctive characteristic of taxi operation in Korea is the rotation (or shift) system that applies to business taxis according to their category. For example, if a city adopts a rotation system of three days, the registered taxis in that city have three categories. Each taxi driver in the city is on-duty for two days and off-duty the third day, continuously. The Passenger Transport Service Act specifies that cities have the authority to determine its taxi rotation system, considering its transport networks and demand for the taxi service. Local governments also can temporarily suspend their rotation system if there is special reason such as the disrupted SMRS, and strikes of the SMRS or intra-city bus companies.

The shift system varies from 3 days to 20 days. Two local government reports from Seoul Metropolitan City and Seongnam city found that most corporate taxis are operated on a shift system with 6 days, while a few cities have 10 days, and most privately-owned taxis work on a shift system of 3 days[5] (Seoul Metropolitan City (2013), Seongnam City (2014)). In other words, a third of privately-owned taxis are available in an emergency totalling some 28,239 in the SCA.

[4] Available at http://www.law.go.kr/eng/engLsSc.do?menuId=1&query=passenger

[5] The major reason for the shift system is to reduce taxi-drivers' fatigue and tiredness-related accidents. Since taxi drivers normally work for 10 to 12 hours a day, suspending the rotation system temporarily would not substantially increase accidents.

Taking into account that all corporate taxis and two thirds of privately-owned taxis equals 95,120, there is an additional 29.7% capacity, compared to an ordinary day. Therefore, providing not too many travellers want to use the taxi as substitute for the disrupted SMRS, they can use taxis with the same difficulty as normal. Table 4-6 shows that mode shares of taxi in the normal situation would be a proper evidence to estimate the shift of users toward taxi.

Table 4-6. Mode Shares of Taxi in the SCA (2013)

	Origin \ Desti.	Seoul	Incheon	Gyeonggi	Outside of SCA	Subtotal
Taxi	Seoul	2,015,224	6,289	100,438	397	2,122,348
	Incheon	4,143	409,512	11,399	52	425,106
	Gyeonggi	92,706	10,718	1,155,267	2,993	1,261,683
	Outside of SCA	448	109	2,647	0	3,203
	Subtotal	2,112,520	426,628	1,269,752	3,441	3,812,341
	Ratio	-	-	-	-	5.9%
Total Mode		29,634,557	6,535,914	27,986,384	777,445	64,934,299

Source: 2014 Revision of Origin/Destination Data in the Seoul Capital Area (adapted, 2017)

Bus services are chiefly classified by route passenger transport business (RPTB) for those with scheduled routes and operation plans for the public, and area passenger transport business (APTB) for chartered buses with no scheduled routes. Passenger Transport Service Act states that chartered buses can supply a service of one transportation contract between the chartered bus company and a contractor, which can be a central government organisation, a local government organisation, a private company, a school or nursery, and so on. In other words, chartered bus is operated with one specific contract for special purpose.

77.9% of chartered bus services are based on long-term contracts e.g. one year, while the remaining 22.1% operate on short-term contracts such as one day or one week, Mo (2012). Table 4-5 shows the number of intra-city bus and chartered buses in the SCA as 20,436 and 20,089 respectively. In an emergency situation of the disrupted SMRS, 22.1% of all chartered buses, 4,440 and about 22% of the all intra-city buses, could be made available at the request of government. Table 4-7 shows that intra-city buses in the SCA transport 10,607,122 travellers per day with an average number of passengers of 13.49 each. Since the capacity of a normal intra-city bus is approximately 50 passengers, seated and standing, there is room for additional 36.51 passengers per bus. This amounts an increase of 70% of the capacity in emergencies. By comparison, only 8,560,588 passengers are carried by the SMRS (see Table 4-2). The conclusion is that there is little capacity problem on the bus services. Whoever wants to take a bus instead of the SMRS can use current scheduled buses or additionally provided chartered buses, although some scheduled buses will be highly congested as well as specific regions. Although chartered buses are probably not distributed equally in the SCA, this research assumes that chartered buses can be provided without considerable delay because of their depot location.

Table 4-7. Mode Shares of Intra-city Bus and Metro Bus in the SCA in trips/day (2013)

(unit: trips/day)

	Origin \ Desti.	Seoul	Incheon	Gyeonggi	Outside of SCA	Subtotal
Intracity Bus	Seoul	4,978,987	6,747	437,110	94	5,422,938
	Incheon	10,743	1,196,195	81,523	39	1,288,501
	Gyeonggi	350,274	47,440	3,493,869	2,792	3,894,375
	Outside of SCA	145	11	1,151	0	1,308
	Subtotal	5,340,150	1,250,394	4,013,653	2,925	10,607,122
	Ratio	-	-	-	-	16.3%
	Origin \ Desti.	Seoul	Incheon	Gyeonggi	Outside of SCA	Subtotal
Metro Bus	Seoul	38,173	30,890	288,281	146	357,490
	Incheon	27,470	20,945	8,908	36	57,360
	Gyeonggi	284,121	5,154	238,505	254	528,034
	Outside of SCA	146	41	248	0	435
	Subtotal	349,910	57,029	535,943	437	943,319
	Ratio	-	-	-	-	1.5%
Total Mode		29,634,557	6,535,914	27,986,384	777,445	64,934,299

Source: 2014 Revision of Origin/Destination Data in the Seoul Capital Area (adapted)

Of course, some travellers abandon their travel because of disruptive events on the SMRS. Marsden *et al.* (2014) and Marsden *et al.* (2016) relate several responses to disrupted transport networks, including cancellation, postponement, delayed start, and working from home. However, our online survey showed that most travellers, especially commuters, would like to continue their original trip by using alternative transport modes. Of the 1,415 participants of the online survey, only 0.6% answered that they would work at home in case of disruption to the SMRS (see Table 6-1). Thus, abandoning original trips is not considered in this work, and fixed demand is assumed for short-term disruptions of one day.

Lastly, the responses of those travellers whose trip purposes are not going to work may cause distorted results. Travellers with other purposes can easily abandon their trips and may be less sensitive to travel time (Storchmann, 2001). The greater the magnitude of the impact of disruptive events, the more the assumption of similarity between commuters' choice and non-commuter's one amplifies the scale of influence. With the difficulty of forecasting relatively sensitive travellers' choices in a disruptive situation and the difficulty of estimating maximum impact on transport networks, this research will assume that the intention of commuters is the same as the choice of a general traveller.

4.5.2 Assumptions about Information on Disruptive Events

This study is based on mode transfer caused by disruptive events on the SMRS. Therefore, it is critical whether travellers know of such a disruption when they determine their transport modes. It has been argued that capacity reduction in transport networks can induce travellers to adapt, such as change of route, adjustment of travel time, change of destination, consolidation of trips, change of transport mode, and so on (Cairns *et al.*, 2002; Guiver, 2011). These adaptations would happen with the provision of exact information about reduced transport capacity or disrupted transport networks. How long does it take for travellers to be informed of the disruptive situation from the Internet, mass media, central/local governments or social network services such as Twitter, and Facebook?

Wendling *et al.* (2013) alleged that five types of social media could be identified. Social network services such as Facebook, Myspace bring groups of people together and help coordination among volunteers and emergency services. Content sharing media, such as Youtube, Flickr allow anyone to upload content such as videos or pictures to be shared with everyone or with a restrictive community of users, helping situational awareness by identifying images or videos of how a crisis is evolving in real time. Collaborating knowledge sharing media such as Wikis and podcasts enable participants to ask questions and waif for answers coming from different users, developing dialogues between different stakeholders in a risk or crisis management situation. Blogging social media are used to share facts and values, emotions and expectations. The blogging or micro blogging tools, such as Twitter, can be used to share facts in real time, but also to convey recommendations and warnings very rapidly. Finally, volunteer technology communities (VTC), such as Ushahidi and Sahana are social media platforms or modules created especially for risk and crisis communication (Wendling *et al.*, 2013).

Among various social network services, Reuter *et al.* (2011) observed the activities of the airlines Lufthansa, EasyJet and AirBerlin on their Twitter and Facebook pages when there was the eruptions of Eyjafjallajokull in Iceland 2010. The observation of the Twitter pages in the period 15th to 22nd April 2010 showed that all three airlines provided news about the flight ban and volcanic ash. Most of the tweets provided a link to the news section of their own homepage. Thus, the subscribers had been constantly informed by the companies. EasyJet showed the greatest activity on Twitter. While AirBerlin published 18 tweets in the same period and answered only three personal questions, Lufthansa tweeted 69times in the same period and answered about 17 personal customer requests. On Facebook, AirBerlin posted news on their own wall but comments posted by users were not widely replied. This shows that AirBerlin did not consider Facebook as a medium for communication with the customer. However, EasyJet and Lufthansa responded to almost all of the questions that were posted on the wall. In other words, social network service like Twitter and Facebook can be used by companies as a broadcast medium (Reuter *et al.*, 2011).

Although much previous research has focused on disaster information, few have identified the speed of propagation of that to the public. Much current literature has only covered social media's reaction to outbreak of huge natural disasters or intentional attacks (Kaigo, 2012; Wilson, 2012; Chatfield and Brajawidagda, 2013; Kim *et al.*, 2013; Allen *et al.*, 2014; David *et al.*, 2016). Some have suggested utilising social media to acquire disaster-related information quickly (Seo *et al.*, 2013; Ishida *et al.*, 2014).

One possible assumption is perfectly delivered information to all travellers. An ideal communication infrastructure for 100% information delivery is the Cell Broadcasting Service (CBS) piggy-backing on the mobile phone system. CBS is a Korean system for natural disasters or emergency situations. Base stations for mobile telecommunication services can simultaneously send a disaster-related message to users of mobile phones without any charge[6]. The geographical area where the urgent information should be delivered can be selected. CBS is made available without recognising individual mobile phone numbers or holders' identities. The Ministry of Public Safety and Security make the decision on whether to send a message, and it has been a requirement for all mobile phones to be set up with the CBS function since 1 January 2013[7]. Considering the penetration of mobile phones and the trend, especially of smart phones, perfectly delivered information of disruptive events is an acceptable assumption (see Table 4-8).

Table 4-8. Ownership of Mobile Phones in Korea

Possession Rate	2011	2012	2013	2014	2015
Mobile Phone (Total)	89.2%	91.2%	91.8%	92.4%	93.2%
Smart Phone	24.2%	54.0%	71.9%	79.5%	83.2%
Non-Smart Phone	75.8%	46.0%	28.1%	20.5%	16.8%

Source: 2015 Possession of Personal Media and Change of Use Pattern, KISDI (2015)

Another realistic assumption is delayed delivery of information to all travellers. In real circumstances, travellers who have been notified would increase with time if there has been no prompt CBS message. For example, a crane overturned near a railway near Bupyeong Station at 2.30 pm on 16 September 2015 (. As a result, 14 stations of SMRS Line 1, from Incheon to Bucheon, were closed down for 15 hours . The first tweet ocurred at 3.08 pm, some tweets were 38 minutes later. The first media report

[6] The CBS is operated without charge by both the Korean government and users of mobile phones. Telecommunication companies provide the CBS as a social responsibility service.

[7] The obligatory installation is based on the article 38-2 of the Framework Act on the Management of Disasters and Safety, Korea. Operation of CBS initially concentrated on natural disasters but the Korean government extended target situations to include transport issues.

was at 3.18 pm, 48 minutes after the event. For one hour following the disruption, very few people knew the situation before they started their journey because no CBS message was sent. Propagating the information undoubtedly speeded up after it was broadcast on the 24/7 news channel, or delivered by social network services. Nevertheless, it is difficult to pinpoint the exact process of dissemination in the real situation.

This research will assume not only perfectly delivered information through a prompt CBS message, but also delayed delivery of that information. For the delayed propagation, we adopt the practical assumption of a gradual increase in notified travellers with time. Additionally, it is assumed that within 12 hours all passengers, including potential travellers, will be fully informed of a disruptive event.

The first 8.33% (one twelfth) of all travellers will have been informed of the disruption within 1 hour of the event. The second 8.33% of all travellers, 16.67% of total passengers cumulatively, will have been notified within 2 hours. Finally, 12 hours later, all travellers can choose their alternative modes to optimise their trips (see Table 4-9).

Table 4-9. Assumptions on Numbers of Informed Travellers by hour

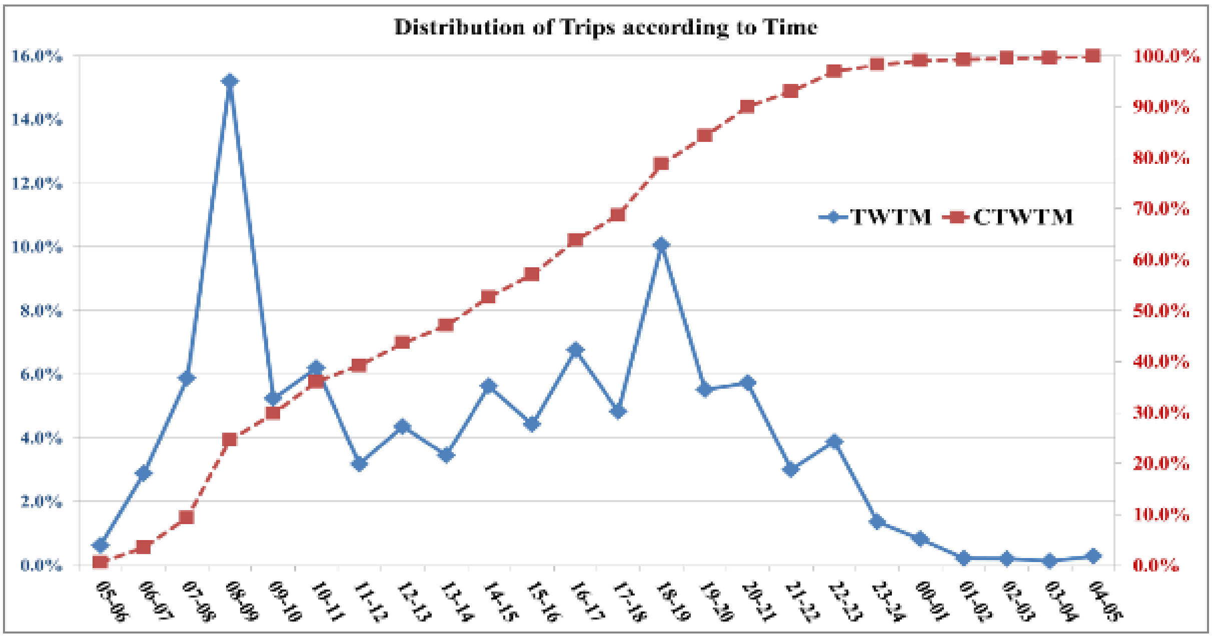
Time	NIRIT	CRUT	CRIT	Time	NIRIT	CRUT	CRIT
05-06	0.0%	100.0%	0.0%	17-18	8.3%	0.0%	100.0%
06-07	8.3%	91.7%	8.3%	18-19	0.0%	0.0%	100.0%
07-08	8.3%	83.3%	16.7%	19-20	0.0%	0.0%	100.0%
08-09	8.3%	75.0%	25.0%	20-21	0.0%	0.0%	100.0%
09-10	8.3%	66.7%	33.3%	21-22	0.0%	0.0%	100.0%
10-11	8.3%	58.3%	41.7%	22-23	0.0%	0.0%	100.0%
11-12	8.3%	50.0%	50.0%	23-24	0.0%	0.0%	100.0%
12-13	8.3%	41.7%	58.3%	00-01	0.0%	0.0%	100.0%
13-14	8.3%	33.3%	66.7%	01-02	0.0%	0.0%	100.0%
14-15	8.3%	25.0%	75.0%	02-03	0.0%	0.0%	100.0%
15-16	8.3%	16.7%	83.3%	03-04	0.0%	0.0%	100.0%
16-17	8.3%	8.3%	91.7%	04-05	0.0%	0.0%	100.0%

Source: 2012 Survey of Passengers' Origin/Destination in the Seoul Capital Area (adapted)

People who have not received the information would be restricted on choice because they only identify unavailability of the SMRS after they arrive at their first station and they would have to continue their trips by choosing a taxi, bus and so on. The online survey shows that uninformed travellers, who have chosen cars for their alternatives, would be redistributed toward other alternative transport modes proportionally. By contrast, travellers who have acquired the information can choose all kinds of alternatives, including their own cars.

Figure 4-7 and Table 4-10 demonstrate that the distribution of trips varies depending on the time of day. There is a morning peak between 8 am and 9 am, and an evening peak between 6 pm and 7 pm as expected. The trip figures from Table 4-10 and assumed information delivery figures from Table 4-9 will be used when revising the O/D data to reflect stated intentions or revealed intentions in the online survey. Since it is sensible to modify the O/D data with the final result of mode choices during a SMRS disruption, we shall assume 'perfectly delivered information'.

Figure 4-7. Distribution of Trips by hour (2011)



TWTM: Trips by Whole Transport Modes, CTWTM: Cumulative TWTM

Source: 2012 Survey of Passengers' Origin/Destination in the Seoul Capital Area (adapted)

Table 4-10. Distribution of Trips by hour (2011)

Time	Trips by all Purposes	Ratio of T.B.P.	Trips by all Modes	Raito of T.B.M.	Time	Trips by all Purposes	Ratio of T.B.P.	Trips by all Modes	Raito of T.B.M.
00-01	469,150	0.8%	516,525	0.8%	12-13	2,510,527	4.5%	2,723,242	4.4%
01-02	137,413	0.2%	141,791	0.2%	13-14	1,981,324	3.5%	2,151,516	3.5%
02-03	132,001	0.2%	135,341	0.2%	14-15	3,304,320	5.9%	3,510,328	5.6%
03-04	89,663	0.2%	91,473	0.1%	15-16	2,592,398	4.6%	2,760,823	4.4%
04-05	181,506	0.3%	184,681	0.3%	16-17	3,941,147	7.0%	4,215,027	6.8%
05-06	369,130	0.7%	398,132	0.6%	17-18	2,713,279	4.8%	3,013,510	4.8%
06-07	1,670,287	3.0%	1,800,162	2.9%	18-19	5,781,697	10.3%	6,271,808	10.1%
07-08	3,244,090	5.8%	3,665,327	5.9%	19-20	2,922,776	5.2%	3,441,095	5.5%
08-09	8,485,672	15.1%	9,470,480	15.2%	20-21	3,145,550	5.6%	3,574,422	5.7%
09-10	2,762,420	4.9%	3,267,635	5.2%	21-22	1,649,131	2.9%	1,875,831	3.0%
10-11	3,509,936	6.2%	3,864,504	6.2%	22-23	2,155,429	3.8%	2,424,106	3.9%
11-12	1,767,306	3.1%	1,982,143	3.2%	23-24	716,747	1.3%	857,019	1.4%
					Sum	56,232,899	100.0%	62,336,921	100.0%

T.B.P: Trips by all Purposes, T.B.M: Trips by all Modes

Source: 2012 Survey of Passengers' Origin/Destination in the Seoul Capital Area (adapted)

4.5.3 Assumptions of Costs to SMRS passengers

Out-of-pocket costs to SMRS passengers are related to the tickets for using the SMRS. If potential travellers can reserve their tickets during disruptive events on the SMRS and use them later, there would be no additional social travel costs. However, if potential travellers cannot use their tickets and they expire due to the SMRS being disrupted, the social travel costs must increase. Therefore, total social travel costs regarding out-of-pocket costs of the SMRS passengers strongly depends on the types of tickets available.

Tickets of the SMRS are classified as: transportation card actioned by radio frequency (RF T.C.), single-use transportation ticket, preferential transportation card, and commuter ticket.

Travellers who want to use RF T.C. can select a prepayment card, or a deferred payment card based on credit card. A prepayment card is charged in advance to 'contain' a certain amount of money to use continuously until the money runs out, when it may be recharged. A deferred payment card is a credit card to which the RF transportation feature has been added, and where the public transportation charge is included in the monthly credit card payment (Seoul Metro, 2017). As the travel costs of the RF transportation card exactly matches the usage of the SMRS, there would be no additional social travel costs for the holders of the RF T.C. during a disruptive event.

The single-use transportation ticket is purchased by travellers at a station, and the fare is determined by destination. Holders of single-use transportation ticket do not incur additional social travel costs during disruptive events on the SMRS since we assume a one-day disruption of a specific SMRS section from 5.00 am to 4.59 am the next day. Even though passengers buy a single-use transportation ticket, they can use it later after the SMRS has recovered. Travellers may obtain a refund from the operators of the SRMS if required.

Table 4-11. Types and Fares of Commuter Tickets in the SMRS

<table>
<tr><th>Types</th><th colspan="8">Fares and sections</th></tr>
<tr><td rowspan="2">For Seoul only</td><td colspan="8">[Fares]
- Fixed price of 55,000 KRW (basic fare of transportation card 1,250 KRW x 44 times)
[Sections]
- Among Seoul Metro Subway Lines 1 through 9 and Airport Railroad, Seoul-Geumcheon-gu Office, Guro-Onsu, Hoegi-Dobongsan, Gajwa-Yangwon, Wangsimni-Bokjeong, Seoul-Susaek, Sangbong-Sinnae, and Gimpo Airport-Seoul on Airport Railroad</td></tr>
<tr><td colspan="8">* With the [Seoul exclusive commuter ticket], it is not possible to get on trains at stations other than Seoul exclusive use sections.Extended sections on Subway 7 between Kkachiul-Bupyeong-gu Office and Moran Station on Seoul Metro's Bundang Line are not Seoul exclusive use sections.</td></tr>
<tr><td rowspan="10">Distance proportional type (14 types)</td><td colspan="8">[Fares]
- Issued at a 15% discounted price from the transportation fare for each type x 44 times; for 1,250-1,450 KRW sections, 1,250 KRW x 44 times is applied.
[Sections]
- Used according to the fares for each type in all sections of Seoul Metro</td></tr>
<tr><td colspan="3">Commuter tickets</td><td rowspan="2">Fares of transportation cards</td><td colspan="3">Commuter tickets</td><td rowspan="2">Fares of transportation cards</td></tr>
<tr><td>Type (stage)</td><td>Fares of commuter tickets</td><td>Distance applied</td><td>Type (stage)</td><td>Fares of commuter tickets</td><td>Distance applied</td></tr>
<tr><td>1</td><td>55,000</td><td>20km</td><td>within 1,450</td><td>8</td><td>80,400</td><td>58km</td><td>2,150</td></tr>
<tr><td>2</td><td>58,000</td><td>25km</td><td>1,550</td><td>9</td><td>84,200</td><td>66km</td><td>2,250</td></tr>
<tr><td>3</td><td>61,700</td><td>30km</td><td>1,650</td><td>10</td><td>87,900</td><td>74km</td><td>2,350</td></tr>
<tr><td>4</td><td>65,500</td><td>35km</td><td>1,750</td><td>11</td><td>91,600</td><td>82km</td><td>2,450</td></tr>
<tr><td>5</td><td>69,200</td><td>40km</td><td>1,850</td><td>12</td><td>95,400</td><td>90km</td><td>2,550</td></tr>
<tr><td>6</td><td>72,900</td><td>45km</td><td>1,950</td><td>13</td><td>99,100</td><td>98km</td><td>2,650</td></tr>
<tr><td>7</td><td>76,700</td><td>50km</td><td>2,050</td><td>14</td><td>102,900</td><td>excess of 98 km</td><td>2,750</td></tr>
</table>

Source: Seoul Metro (2017)

The preferential transportation card is for those who travel the SMRS free of cost. This free card is used by citizens older than 65, handicapped people, and people who are recognised for national merit (Seoul Metro, 2017). Since there is no out-of-pocket cost for this ticket, it can be assumed that there is no change of social travel costs during a disruptive event.

The commuter ticket is a kind of monthly season ticket provided by the operators of the SMRS. The price of a commuter card is 2,500 KRW and the card can be charged to 'contain' a certain amount of money. It can be used up to 60 times within 30 days of the date charged. After 30 days have passed or 60 rides have been taken, the card expires. Table 4-11 shows the two types of commuter ticket: for Seoul only, and distance proportional type. The commuter ticket for Seoul is valid only within Seoul Metropolitan City, while the distance proportional ticket can be used within the SCA and is priced according to its distance (Seoul Metro, 2017).

It is important to identify change of social travel costs by commuter tickets during any disruption. Since commuter tickets allow 60 trips within 30 days, one day's disruption does not produce much impact on social travel costs, and only 1.9% of travellers use commuter tickets anyway. In other words, 98.1% of travellers use other types of ticket (see Table 4-12). Jeong *et al.* (2017) showed that the proportion of commuter tickets in the Seoul Metro Lines had decreased from 3.6% in 2012 to 3.0% in 2015 (see Table 4-13). Therefore, this work will assume that there is no additional total social travel cost from out-of-pocket costs on the SMRS.

Table 4-12. Proportion of Commuter Tickets in the SMRS

RF T.C.	Single Use	Preferential	Commuter	Total
908,868,085	18,971,873	182,985,616	21,950,302	1,132,775,876
80.2%	1.7%	16.2%	1.9%	100.0%

Source : KORAIL (2016)

Table 4-13. Proportion of Commuter Tickets in the Seoul Metro Lines

Year	2012	2013	2014	2015
Commuter Tickets' Ratio	3.6%	3.2%	3.0%	3.0%

Source: Jeong *et al.* (2017, p.3)

4.5.4 Limits to Additional Social Travel Costs

It is common procedure in the field of transport infrastructure to analyse social benefits and social costs with diverse parameters. When total social benefits and costs are estimated, the following is taken into account: the value of travel time; reduced operating costs for vehicles (saved fuel, saved engine oil and decreased tyre wear); fewer car accidents; and curtailed environmental costs related to the emission of pollutants. However, the revenue from transport fares is not included as a social benefit because it is regarded as the relocation of social resources. In other words, reduced revenue of SMRS due to transferred passengers caused by a disruptive event will not be taken into account as a change in social travel costs. Additionally, during the process of mode choice during a disruption, any subsidies from government to private sectors are also regraded as pecuniary transfers (see, for example, Sugden, 1972).**Error! Reference source not found.**Table 4-14 focuses on the choice of car instead of a disrupted SMRS and illustrates what the TSTC took into account and what was excluded as pecuniary transfers,. The reduced fare revenue of the SMRS operators arises from the unpaid fares of the travellers who avoid/cannot use the SMRS when it is not available. This is a typical example of pecuniary transfer. However, some reduced operating cost of the SMRS should be considered in calculating the TSTC. From the perspective of users and cars, the increased travel time is a major element of the TSTC. Increased operating cost of the car driver and parking costs also need to be included. Further, the costs of increased road traffic accidents and the increased environmental impact costs should be taken included.

Table 4-14. Costs/Benefits due to the choice of Car instead of the Disrupted SMRS

Classification		Cost		Benefit	
Operator	SMRS		(reduced rail fares)	√	reduced operating cost
User	SMRS	√	increased travel time		(reduced rail fares)
	Auto	√	increased travel time		
		√	increased operating cost (fuel, engine oil, wear of tyre, depreciation)		
		√	increased parking cost		
Society	Auto	√	increased traffic accidents		
		√	increased environmental impacts		

√: taken into account for the TSTC

( ): pecuniary transfer excluded from the TSTC

Table 4-15, Table 4-16, and Table 4-17 show pecuniary transfers and factors for the TSTC with the different alternative modes of scheduled bus, chartered bus, and taxi.

Table 4-15. Costs/Benefits due to the choice of Scheduled Bus instead of the Disrupted SMRS

Classification			Cost		Benefit
Operator	SMRS		(reduced rail fares)	√	reduced operating cost
	Regular Bus	√	increased operating cost (fuel, engine oil, wear of tyre, depreciation)		(increased bus fares)
User	SMRS	√	increased travel time		(reduced rail fares)
	Regular Bus		(increased bus fares)		
		√	increased travel time		

√: taken into account for the total social travel costs

( ): pecuniary transfer that was excluded in the total social travel costs

Table 4-16. Costs/Benefits due to the choice of Other Bus instead of the Disrupted SMRS

Classification			Cost		Benefit
Operator	SMRS		(reduced rail fares)	√	reduced operating cost
	Other Bus	√	increased operating cost (fuel, engine oil, wear of tyre, depreciation)		(increased bus fares)
					(subsidy by local government)
User	SMRS	√	increased travel time		(reduced rail fares)
	Other Bus		(increased bus fares)		
		√	increased travel time		
Society	Other Bus		(subsidy by local government)		
		√	increased traffic accidents		
		√	increased environmental impacts		

√: taken into account for the total social travel costs

( ): pecuniary transfer that was excluded in the total social travel costs

Table 4-17. Costs/Benefits due to the choice of Taxi instead of the Disrupted SMRS

Classification		Cost		Benefit	
Operator	SMRS		(reduced rail fares)	√	reduced operating cost
	Taxi				(increased taxi fares)
User	SMRS	√	increased travel time		(reduced rail fares)
	Taxi		(increased taxi fares)		
		√	increased travel time		
		√	increased operating cost (fuel, engine oil, wear of tyre, depreciation)		
Society	Taxi	√	increased traffic accidents		
		√	increased environmental impacts		

√: taken into account for the total social travel costs,

( ): pecuniary transfer that was excluded in the total social travel costs

In this work, a changed value of travel time will be selected as a representative factor for social costs. In addition, operating costs of car travellers, operating costs of the SMRS, road traffic accidents costs, environmental impact costs, and parking costs will be taken into account in assessing the integrated vulnerability of transport networks.

4.6 Summary

This chapter firstly explained the integrated vulnerability of transport networks with the concept of social total travel costs. In order to analyse exactly vulnerability of transport networks, it is necessary to take into account disruption's impact on both transit networks and road networks.

Next, the research methodology has been elaborated, from the analysis process to the several assumptions needed. Regarding the research procedure, the first things to be done were to collect data about transport networks in the SCA and to conduct an online survey of stated intentions during a disruptive event on the SMRS.

With these results, the integrated vulnerability of transport networks in the SCA will be assessed using the TransCAD program. The process of TransCAD analysis is mainly made up of six steps: data collection, creation of road networks, trip assignment on road networks, creation of the SMRS networks, trip assignment on the SMRS networks, and summary of analysis result.

Additionally, expert interviews will be undertaken in order to outline management strategies for a more resilient transport network in the SCA. Interviewees would be selected as several experts who have been involved with the operation of the SMRS or policy-maker of railway networks. Researchers in the field of transport networks analysis will also be contacted for the expert interviews.

Finally, the assumptions underlying this work were addressed, because of insufficient information about transport networks in the SCA and for the efficiency of analysis: assumptions about mode transfer, assumptions about information on disruptive events, assumptions of costs to SMRS passengers, and limits to additional social travel costs.

Chapter 5 Total Social Travel Costs

The TSTC is a crucial concept in defining the integrated vulnerability of transport networks. In order to choose appropriate components for the TSTC, it is important to identify the differences between the normal situation and a disrupted situation of transport networks in the SCA.

Firstly, travel times will change due to a non-available section of the SMRS. If travellers choose cars as their alternative mode, operating costs of travellers would also change. Reduced services on the SMRS can change the operating costs of the SMRS. Augmented traffic on road networks can increase the social cost from additional road traffic accidents and vehicle exhaust emissions. Also, increased parking spaces are required for the increased road traffic, especially for cars in urban areas. These six categories are mainly used to identify benefits for a newly-planned infrastructure projects during a feasibility study.

TSTC is defined by Equation 5-1. for the normal situation. TSTC for a disrupted situation will be calculated to determine the difference and used as an index of integrated vulnerability of transport networks.

$$TSTC = \sum TSTC_{t,t} + TSTC_{op.road} + TSTC_{op.SMRS} + TSTC_{t.a} + TSTC_{env} + TSTC_{par} \quad (5\text{-}1)$$

$TSTC_{t.t}$: total social travel costs from travel time costs (unit: KRW)

$TSTC_{op.road}$: total social travel costs from operating costs of road networks (unit: KRW)

$TSTC_{op.SMRS}$: total social travel costs from operating costs of the SMRS (unit: KRW)

$TSTC_{t.a}$: total social travel costs from road traffic accident costs (unit: KRW)

$TSTC_{env}$: total social travel costs from environmental impact costs (unit: KRW)

$TSTC_{par}$: total social travel costs from car travellers’ parking costs (unit: KRW)

The details of these six TSTC terms are now elaborated.

5.1 TSTC from Travel Time Costs

First we address $TSTC_{t.t}$ can be measured. In order to define $TSTC_{t.t}$ for a disruptive event on the transport networks, it is necessary to understand the concept of the value of travel time (VTT), a primary parameter when the benefit of a transport infrastructure project is evaluated for economic feasibility. VTT is generally defined as a willingness to pay (WTP) for the saving of travel time by using a newly-constructed infrastructure, or by-passing a toll-charged road section, and so on. VTT usually varies by travel purpose, travel distance, the time of travelling, and income level of travellers (Kim *et al.*, 2014).

Although there are several methods to estimate VTT (Wardman, 1998; Abrantes and Wardman, 2011), all the public infrastructure projects in Korea follow the guideline for a preliminary feasibility study from the Korea Development Institute[8]. KDI has performed all the preliminary feasibility studies for publicly-financed infrastructure projects having total project costs of more than 50 billion KRW.

Table 5-1illustrates the VTT that has been applied to all publicly-financed projects. All the values of current standard were calculated from the VTT in 2013 using consumer price index (CPI) of 2014 and 2015. The average value of travel time (AVTT) for cars/taxis, buses and trucks in 2015 are 15,255 KRW/vehicle-hr, 90,736 KRW/vehicle-hr and 16,704 KRW/vehicle-hr respectively. Travellers on SMRS have an AVTT of 6,039 KRW/vehicle-hr.

Table 5-1. Value of Travel Time in Korea

Classification	Base Year	Unit	Cars/Taxis		Buses			Truck	SMRS (perperson)	
			B	NB	D	B	NB	B	B	NB
Passenger	2013	Person/vehicle	0.22	1.02	1.00	0.23	13.26	1.00	0.05	0.95
Value of Travel Time	2013	KRW/man-hour	22,775	9,748	17,260	22,775	5,011	16,374	22,775	5,033
		KRW/vehicle-hr	5,011	9,943	17,260	5,238	66,446	16,374	1,139	4,781
Average Value of Travel Time	2013	KRW/vehicle-hr	14,954		88,944			16,374	5,920	
	2014	KRW/vehicle-hr	15,148		90,100			16,587	5,997	
	2015	KRW/vehicle-hr	15,255		90,736			16,704	6,039	

Source: KDI (2016), Guideline for the Preliminary Feasibility Study, Korea

B: Business, NB: Non-Business, D: Driver

[8] Korea Development Institute (KDI) is a major national institute. It was established in 1971 to conduct policy research and analysis on fundamental economic and social issues using scientific methods to support the nation's development efforts. KDI has conducted rigorous research on a broad range of economic and social issues, from macroeconomics policy, fiscal policy, finance, welfare, labour, trade, competition policy, to the North Korean economy.

Average value travel time in 2014 = value for 2013 × CPI (101.30)

Average value travel time in 2015 = value for 2014 × CPI (100.71)

These values vary slightly depending on the prevailing socio-economic conditions. In other words, AVTT are different depending on how the value of travel time by average household income, minimum wage per hour, employment, and so on, is assessed (U.S. Department of Transportation, 2016). For example, the AVTT of trips for work was £22.69/man-hour in the UK in 2013, equivalent to 31,766 KRW, compared with 22,775 KRW for Korea (Department for Transport, 2016). For France, the same measure was €18.84/man-hour, equivalent to 24,495 KRW (Meunier and Quinet, 2015). In the USA, this AVTT was $24.90/man-hour, equivalent to 27,386 KRW (U.S. Department of Transportation, 2016). Consequently, the AVTT of Korea was significantly smaller than these developed countries.

With the introduction of averaged values of travel time, total TSTC from travel time can be defined. For all transit networks routes, there are unique passenger numbers and travel times for each route. For all the of road networks links, there are unique vehicle numbers corresponding to transport modes and travel time for each link. If the AVTT for each transport mode is multiplied by travel time and volumes of passengers or vehicles, a summation of the result can be called the total travel cost in specific transport networks.

Equation 5-2 the calculation of $TSTC_{t.t}$ with the various parameters of transport networks defined below. Fundamentally, $TSTC_{t.t}$ is a summation of product with traffic flows, travel time and value of travel time. One should be careful not to discard incoming or outgoing travel in transit networks. Waiting time and transfer time must also be taken into account for transit networks. It is possible to calculate two $TSTC_{t.t}$ values: one is for the normal situation of transport networks in the SCA; the other is during disrupted transport networks.

$$TSTC_{t.t} = \sum_{m=1}^{M} \sum_{l=1}^{L} \{(Vol_{m,l}) \times (TT_{m,l}) \times (VTT_m)\} + \sum_{r=1}^{R} \{(Pass_r) \times (TT_r) \times (VTT_{pass})\} + \sum_{l=1}^{L} \{(Travel_l) \times (TT_l) \times (VTT_{travel})\} \tag{5-2}$$

where

$TSTC_{t.t}$: total social travel costs from travel time costs (in KRW/day)

$Vol_{m,l}$: volume of transport mode *m* on link *l* of road networks[9] (in vehicles)

$TT_{m,l}$: travel time of transport mode *m* on link *l* of road networks (in hours)

VTT_m : value of travel time of transport mode *m* (in KRW/vehicle-hr)

$Pass_r$: number of boarding passengers on route *r* of the SMRS (in persons)

TT_r : travel time of route *r* of the SMRS (unit: hours)

VTT_{pass} : value of travel time of passengers of the SMRS (in KRW/man-hours)

$Travel_l$: number of travellers who enter the SMRS, transfer within SMRS, and leave the SMRS on link *l* of road networks (in persons)

TT_l : travel time of route *l* of road networks (in hours)

VTT_{travel} : value of travel time of travellers enter/within/leave the SMRS (unit: KRW/man-hours)

M : total transport modes of road networks (car, bus with scheduled operation, other bus including chartered bus, taxi, truck)

L : total links of road networks (including all transfer routes within the SMRS)

R : total routes of the SMRS

[9] Links of road networks include all transfer routes within Seoul Metropolitan Railway Systems.

5.2 TSTC from Operating Costs of Road Networks

The second term in Equation 5-1 is a TSTC from operating costs of road networks. If there is a disrupted event on the SMRS, it is possible for traffic volumes on road networks to increase, and increased travel time, which means increased operating costs for car users.

When it comes to operating cost of road networks, fuel, engine oil, tyre wear, and depreciation, are typical items applied to operating cost. Normally, these are largely determined by vehicle speed and type. Therefore, operating costs ($TSTC_{op.road}$) are defined by the unit operating cost per vehicle-km, length of links, traffic volumes for each transport mode (Equation 5-3). The Guideline for feasibility studies of transport facilities in Korea suggest the function of unit operating cost per vehicle-km is a third degree function of vehicle speed. Coefficients of the function can be determined by the regression method using all values of Table 5-2 and Table 5-3 (MOLIT, 2013).

$$TSTC_{op.road} = \sum_{m=1}^{M}\sum_{l=1}^{L}\left(o_{m0} + o_{m1} \times Speed_{m,l} + o_{m2} \times {Speed_{m,l}}^{2} + o_{m3} \times {Speed_{m,l}}^{3}\right) \times Length_{l} \times \left(Vol_{m,l}\right) \tag{5-3}$$

where

$TSTC_{op.road}$	: total social travel costs from operating costs of car travellers (in KRW/day)
o_{mi}	: coefficients of operating cost functions by mode *m* (*i* = 0, 1, 2, 3)
$Speed_{m,l}$	: speed of transport mode *m* on link *l* of road networks (in km/hour)
$Length_l$	: length of link *l* of road networks (in km)
$Vol_{m,l}$	: volume of transport mode *m* on link *l* of road networks, including all transfer routes within SMRS (in vehicles)
M	: total transport modes of road networks (car, bus with scheduled operation, other bus including chartered bus, taxi, truck)
L	: total links of road networks (including all transfer routes within SMRS)

According to Table 5-2 and Table 5-3, the operating cost of car is the lowest and large goods truck marks the highest cost among all types of road vehicles. Generally speaking, the larger the vehicle, the more expensive it costs to operate. One interesting finding is that there is an optimal speed which minimises the operating cost of vehicle, and these are different for each type of vehicle. For example, a car's optimal running speed may be 100 km/h, but a large goods truck may experience its lowest operating cost at 80 km/h. Another remarkable feature is that the other factors of operating cost are also different according to speed. Depreciation is lowest at the speed of 100 km/h, but fuel cost of car is lowest at 70 km/h. Tyre wear cost rises as the speed increases. This work adopts the same the guideline from the KDI and the MOLIT for the function of total operating cost of each vehicle with speed (MOLIT, 2013; KDI, 2016).

In fact, the values of operating costs in Table 5-2 and Table 5-3 were modified by using original data from De Weille (1966) and road statistics in Korea. His study for the World Bank's guidelines and his research has been an important foundation in estimating operating costs of road networks (Chatti and Zaabar, 2012; Han and Kobayashi, 2013).

The UK government provides transport analysts with the Web TAG data book for estimating operating costs of road networks (Department for Transport, 2016). According to Web TAG Table A1.3.8, fuel consumption is estimated using the function seen in Equation 5-4.

$$L = \frac{a}{v} + b + c \times v + d \times v^2 \quad (5\text{-}4)$$

L	: fuel consumption (in *l*/km)
a, *b*, *c*, *d*	: parameters defined for each vehicle category
v	: average speed (in km/hour)

Non-fuel vehicle operating costs are also suggested in Web TAG Table A1.3.14, including oil, tyres, maintenance, depreciation, and vehicle capital saving (only for vehicles in working time).

Table 5-2. Unit Operating Costs – Part 1 (2011)

(Unit: KRW/veh.-km, 2011)

Costs / Vehicle	Speed	Fuel	Engine Oil	Wear of Tyre	Other Manage.	Depreciation	Sum
Auto	10	151.06	2.72	1.02	7.29	349.8	511.89
	20	96.57	2.27	1.87	8.62	298.13	407.46
	30	74.34	1.97	2.88	10.2	254.41	343.81
	40	62.86	1.66	4.19	10.6	214.65	293.96
	50	56.42	1.66	5.35	11.94	182.84	258.21
	60	52.9	1.66	6.79	12.6	164.95	238.9
	70	51.43	1.66	8.37	13.26	151.04	225.76
	80	51.7	1.51	10.11	14.58	135.15	213.05
	90	53.75	1.36	12.28	14.98	125.21	207.59
	100	58.05	1.66	14.59	15.91	116.48	206.69
	110	65.76	2.11	17.76	17.64	106.53	209.79
	120	79.67	3.17	21.1	19.23	94.2	217.38
Mini-bus	10	218.43	3.87	0.78	8.57	464.1	695.75
	20	137.74	3.5	1.43	9.68	383.4	535.76
	30	105.52	3.13	2.33	10.65	314.79	436.42
	40	89.06	2.76	3.26	10.98	262.33	368.38
	50	79.9	2.76	4.18	12.08	226	324.92
	60	74.98	2.57	5.21	12.63	199.77	295.17
	70	73.03	2.4	6.5	13.18	179.6	274.7
	80	73.61	2.21	7.93	14.28	161.45	259.48
	90	76.86	2.02	9.64	15.71	148.12	252.34
	100	83.53	2.02	11.46	16.92	137.2	251.13
	110	95.53	2.21	13.93	18.34	125.12	255.12
	120	117.65	2.57	16.92	19.77	115.02	271.93
Bus	10	530.57	6.22	2.07	10.21	401.55	950.62
	20	378.36	5.32	3.35	11.72	349.75	748.51
	30	306.23	4.54	4.9	13.08	284.98	613.74
	40	266.5	4.15	6.83	13.52	233.16	524.18
	50	243.7	3.76	9.14	15.48	198.18	470.27
	60	231.54	3.5	11.86	17.28	174.87	439.06
	70	227.34	3.23	14.97	18.03	159.33	422.9
	80	230.27	2.98	19.1	21.04	142.48	415.87
	90	240.9	3.37	23.87	23	125.65	416.79
	100	261.52	4.02	29.55	24.5	112.7	432.28
	110	297.55	4.93	35.87	26.01	102.33	466.68
Light Truck	10	204.42	3.81	0.92	8.48	247.59	465.22
	20	149.13	3.45	1.68	9.56	204.53	368.35
	30	122.86	3.08	2.75	10.54	167.94	307.17
	40	108.79	2.73	3.81	10.87	139.95	266.14
	50	101.37	2.73	4.88	11.95	120.55	241.49
	60	98.45	2.54	6.1	12.5	106.56	226.15
	70	99.31	2.37	7.62	13.04	95.81	218.15
	80	104.15	2.17	9.3	14.13	86.12	215.88
	90	114.25	2	11.27	15.54	79.01	222.07
	100	132.91	2	13.43	16.74	73.2	238.27

Source: MOLIT (2013)

Table 5-3. Unit Operating Costs– Part 2 (2011)

(Unit: KRW/veh.-km, 2011)

Costs / Vehicle	Speed	Fuel	Engine Oil	Wear of Tyre	Other Manage.	Depreciation	Sum
Medium Goods Truck	10	420.86	4.52	1.92	10.71	315.76	753.77
	20	285	4.09	3.03	11.4	267.16	570.69
	30	227.91	3.64	4.29	12.11	234.79	482.75
	40	199.49	3.2	5.89	12.87	198.37	419.81
	50	185.73	2.91	7.81	14.22	174.07	384.74
	60	181.76	2.63	9.71	15.22	155.85	365.16
	70	186.36	2.47	11.78	17.09	141.69	359.4
	80	200.97	2.18	14.65	18.72	129.53	366.04
	90	230.82	2.47	17.52	20.77	118.62	390.2
	100	291.12	2.77	21.02	22.24	110.51	447.66
Large Goods Truck	10	751	8.34	2.97	13.82	336.83	1112.97
	20	568.34	7.46	5.16	17.45	276.68	875.1
	30	474.19	6.39	7.81	20.73	228.55	737.67
	40	420.24	5.69	11.09	21.82	192.48	651.32
	50	388.84	5.24	14.54	22.9	159.99	591.51
	60	372.4	4.7	19.22	25.45	138.33	560.1
	70	367.61	4.18	24.06	25.45	123.91	545.2
	80	373.6	3.47	30.62	29.08	108.26	545.04
	90	391.48	3.73	38.58	33.81	105.86	573.47
	100	424.89	4.18	47.34	37.45	95.04	608.9

Source: MOLIT (2013)

5.3 TSTC from Operating Costs of the SMRS

In general, operating costs in the transport industry are a function of capital and labour, the interest rate, and the wage rate. Many researchers have tried to determine specific relationships between actual operating costs of railway networks and transport characteristics as well as physical properties of railway networks.

Viton (1993) tried to identify a cost function of urban rail rapid transit, mainly based on the price of labour, the price of energy, and the ratio of carriages to miles of track. His target cities were New York, Chicago, Philadelphia. Savage (1997) considered a production function of transit service with five factors: way and structure, carriage, train operation labour, propulsion electricity, and automation equipment. He focused on economies of density and economies of system sizes. Savage's (1997) approach was revised by Graham *et al.* (2003) and Graham (2008). Cantos and Maudos (2000) studied the operating costs of railway networks in 15 European countries with variables such as labour costs, fuel and energy, the consumption of materials, the number of passenger-kilometres, freight ton-kilometres. Farsi *et al.* (2005) identified the operating cost function of the Swiss railway companies with these variables: the numbers passenger-kilometres and ton-kilometres, the length of railway networks, and the prices of capital, labour and energy. Wang and Liao (2006) used labour, vehicles, materials, and other intermediate inputs, and the number of passengers and freight transport, as major variables of the function of operating costs for the Taiwan Railway. Harmatuck (2008) tried to pinpoint the operating costs of light rail in the USA by using the number of passengers, the number of trains, revenues, density of the networks, capacity of trains, and the price of labour and energy. Tsai *et al.* (2015) studied driving factors of the operational efficiency of urban rail systems, including technical efficiency as well as cost efficiency. From all this, it is possible to ascertain that there is no single model that can explain exactly the real operating costs for all countries.

The Guideline for Estimating Operating Costs of Railway in Pre-Feasibility Study is used for estimating the operating costs of railway networks in Korea (KDI, 2015). These normally consist of personal expenses, costs of power and electricity, maintenance expenses, general management expenses, and alternative investment costs for trains and railway infrastructure. These components are mainly determined by demands for railway, route length, capacity of trains, headway of trains, operation schedules and frequency, and location of carriage depots.

KDI's guideline says that personal expenses are determined by average payroll costs, after estimating the number of sales staff, operation staff, maintenance staff, and managerial staff. Costs of power and electricity are divided into power costs for train operating, and electric costs for stations and carriage depots. Maintenance expenses for the heavy rail transit (HRT) may be as much as 499.1 million

KRW/year/km for double track overpass or tunnel sections. Unit maintenance cost of the HRT on ground sections was 249.55 million KRW/year/km for double track. In case of the light rail transit (LRT), the maintenance expense proposed was 445.55 million KRW/year/km for double track[10]. General management expenses are estimated as 13% of the combine d total of personnel expenses, costs of power and electricity, and maintenance expenses, which cover the operation of organisation, employee welfare cost, and incidental expenses (KDI, 2015).

Kim *et al.* (2016) modelled the operating costs function in a remarkable research study on the railway networks in Korea. They developed an operating costing model derived with five independent variables: average distance between stations, daily train operation distance, total passenger capacity of a train, driving mode (manned/unmanned), and investment type (public/private). They verified the correlations between operating costs and these variables, which are shown in Table 5-4 and Table 5-5. The five independent variables were selected as the most highly-linked factors with operating costs of railway networks in the SCA.

Table 5-4. Operating Characteristics of Seoul Metro Line 1-4 (2015)

Classification		Seoul Metro Line 1	Seoul Metro Line 2	Seoul Metro Line 3	Seoul Metro Line 4
Section		Seoul St. - Cheongyangri St.	Seongsu St. (Circulation)	Gichuk St. - Ogyeum St.	Danggogae St. - Namtatryeoung St.
Length(km)		7.8	60.2	38.2	31.7
Stations		10	50	34	26
Average Distance between Stations (m)		867	1229	1156	1268
Travel Time (minutes, one way)		16	87	67.5	53
Schedule Speed (km/h)		29.3	33.7	34	35.9
Carriage	Train Set (Set)	16	88	49	47
	Trains (Unit)	160	834	490	470
Operation Interval on weekdays (minutes)	Peak Hours	3	2.5	3	2.5
	Non-Peak Hours	5	5.5	6.5	5.5
Train Operation Distance on weekdays (km)		4032.6	25371.1	15203.6	15279.4
Operation Frequency (No. /day)	Weekday	517	988	398	482
	Saturday	480	894	350	420
	Sunday or National Hollidav	480	838	350	420
Capacity of Train Set		1600	1600	1600	1600
Train Set in Service	Peak Hours	13	70	46	44
	Non-Peak Hours	8	32	22	20
Driving Mode		Manned	Manned	Manned	Manned
Investment Type		Public Financed	Public Financed	Public Financed	Public Financed
Size of Carriage		Heavy Rail Transit	Heavy Rail Transit	Heavy Rail Transit	Heavy Rail Transit

[10] Since the LRTs in the SCA were constructed as overpass structures and have been operated as the ATG (Automated Guided Transit) type, the average maintenance expense is relatively high and is approximately 90% of that of the overpass section of HRT (KDI, 2015).

Table 5-5. Operating Characteristics of Seoul Metro Line 5-8 (2015)

Classification		Seoul Metro Line 5	Seoul Metro Line 6	Seoul Metro Line 7	Seoul Metro Line 8
Section		Banghwa St. - Sangildong St. /Macheon St.	Ueongam St. - Bonghwasan St.	Jangam St. - Bupyeonggucheong St.	Amsa St. - Moran St.
Length(km)		52.3	35.1	57.1	17.7
Stations		51	38	51	17
Average Distance between Stations (m)		1046	949	1142	1106
Travel Time (minutes, one way)		83.5/87.5	69.3	104.5	31.5
Schedule Speed (km/h)		35.8	30.4	32.8	33.7
Carriage	Train Set (Set)	76	41	70	20
	Trains (Unit)	608	328	561	120
Operation Interval on weekdays (minutes)	Peak Hours	2.5	3.5	2.5	4.5
	Non-Peak Hours	6.0	8.0	6.0	8.0
Train Operation Distance on weekdays (km)		23430.4	12495.6	24039.1	5416.2
Operation Frequency (No. /day)	Weekday	448	356	421	306
	Weekends including National Hollidays	368	279	353	270
Capacity of Train Set		1280	1280	1280	960
Train Set in Service	Peak Hours	60	35	62	15
	Non-Peak Hours	28	18	30	8
Driving Mode		Manned	Manned	Manned	Manned
Investment Type		Public Financed	Public Financed	Public Financed	Public Financed
Size of Carriage		Heavy Rail Transit	Heavy Rail Transit	Heavy Rail Transit	Heavy Rail Transit

Source: Kim *et al.* (2016), Seoul Metropolitan Railway Transit Corp. (2015)

Average distance between stations varies from 867 m to 1,268 m. However, daily train operation distances varied considerably according to each line's length. Seoul Metro Line 2 and Seoul Metro Line 7 experienced relatively long train operation distances of 25,371 km/day and 24,039 km/day respectively. Capacity of one carriage is 160 passengers. The train set is 10 carriages long for Seoul Metro Lines 1, 2, 3, and 4, whilst a rake of 8 carriages is linked for Seoul Metro Lines 5, 6, and 7.

Kim *et al.* (2016) suggested the operating costs function, Equation 5-5. Their analysis showed that, daily train operation distance was most highly correlated with the operating costs of the SMRS, followed by total passenger capacity of a train, and driving mode.

$$TSTC_{op.SRMS} = \frac{1}{365}(1{,}408.866 - 4.17X_1 + 0.9097X_2 + 5.0766X_3 + 2{,}695.2148X_4 + 2{,}018.4387X_5) \quad (5\text{-}5)$$

$TSTC_{op.SMRS}$: operating costs of the SMRS per day (in million KRW/day)

X_1 : average distance between stations (in m)

X_2 : daily train operation distance (in km/weekday)

X_3 : total passenger capacity of a train

X_4 : driving mode (0: unmanned, 1: manned)

X_5 : investment type (0: privately financed, 1: publicly financed)

The coefficient of determination (R^2) of this model was 0.971 and t-values of the variables from X_1 to X_5 were–3.474, 18.187, 5.558, 4.415, and 4.159 respectively. These values indicate the good fit of the operating costs function. The model explains about 97% of variation in the data and all parameters are significant at the 5% level (Kim *et al.*, 2016).

Table 5-6 summarises the real operating cost of each Seoul Metro Line. These values could be useful to identify the goodness of fit for estimating the operating costs of future projects, which can be done by the root mean square error (RMSE). The RMSE between the real operating costs of the Seoul Metro Lines and the estimated operating costs by Kim *et al.* (2016) was computed as 25,978 million KRW, equivalent to 0.012 of the real operating costs of the Seoul Metro Lines.

Table 5-6. Real Operating Costs of the Seoul Metro Lines in million KRW (2015)

					unit: million KRW (2015)	
Seoul Metro	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Line 1	167,633	162,682	177,407	170,452	186,820	187,852
Line 2	377,860	366,701	399,892	384,215	421,109	423,435
Line 3	289,607	281,054	306,494	294,478	322,755	324,538
Line 4	303,530	294,566	321,228	308,635	338,271	340,140
Line 5	261,616	279,965	289,957	315,571	327,443	333,789
Line 6	175,302	187,596	194,292	211,455	219,410	223,663
Line 7	224,290	240,020	248,587	270,547	280,725	286,166
Line 8	76,647	82,023	84,950	92,455	95,933	97,792

Source: Park (2008), Kim *et al.* (2016), Financial Supervisory Service of Korea (2016)

Table 5-7 compares operating costs of the Seoul Metro Lines: real data, pre-feasibility guideline of KDI, and estimated by Kim *et al.* (2016). The pre-feasibility guideline of KDI produced low estimate compared to real operating costs. On the other hand, the modelling of Kim *et al.* (2016) suggested a much closer estimate of the operating costs.

Table 5-7. Comparison of Operating Costs of the Seoul Metro Lines in million KRW (2015)

			unit: million KRW (2015)
Seoul Metro Lines	**Real**	**Pre-Feasibility Guideline of KDI, Korea**	**Kim et al (2016)**
Line 1~4	1,275,965	869,747	1,253,835
Line 5~8	941,410	661,693	912,084

Source: KDI (2015), Kim *et al.* (2016)

To estimate operating costs requires two methodologies: estimating each variable by unit cost, and modelling the operating costs function. Although these methods may produce a close estimate of total operating costs of specific railway networks annually, quarterly or monthly, it is difficult to identify the portion of operating costs that is produced by a specific disruptive event on the networks. There is only the figure for overall maintenance costs, without any distinction between normal maintenance and emergency situations. Moreover, we have assumed a suspended section of the specific SMRS Line from station A to station B, without considering the reason behind the event. In other words, it is impossible to calculate how much cost is incurred by the operators of the SMRS in their recovery from disruptive situations. However, it is clear that operating costs of the SMRS can be reduced by shortened operations, except for the costs of recovering the suspended section.

Thus, this work will include only the changes in operating costs due to curtailed operation of a section of the SMRS, not taking recovery costs into account. The operating costs function suggested by Kim *et al.* (2016) will be used to identify the change in operating costs.

5.4 TSTC from Road Traffic Accident Costs

The fourth term in the total social travel costs is a TSTC from road traffic accident costs. If there is a disrupted section of the SMRS, it seems likely that traffic accidents may increase due to added vehicles on the road networks in the SCA.

Road traffic accidents can be defined as events that cause loss of life or property due to interactions between human factors, physical characteristics of transport networks, and environmental aspects. Costs of traffic accidents are not limited only to drivers, vehicles, and other damage. Administration fees for the police and insurance companies should also be included. Additionally, PGS costs, (pain, grief, and suffering), are present as well for families or relatives of the injured (MOLIT, 2013; KDI, 2016).

Total social travel costs from road traffic accidents, $TSTC_{t.a}$, are shown in Equation 5-6. Table 5-8 gives the unit traffic accident occurrence rates by type of road, while Table 5-9 gives the unit costs of traffic accidents. The figures in Table 5-9 are divided into damage to people and damage to non-people, each category being subdivided by pure accident costs, administration fees for police, administration fees for insurance companies, and PGS costs.

$$TSTC_{t.a} = \sum_{at=1}^{AT} \sum_{rt=1}^{RT} \sum_{l=1}^{L} (UTAOR)_{at,rt} \times (UTACR)_{at,rt} \times Length_l \times (Vol_l) \qquad (5\text{-}6)$$

where

$TSTC_{t.a}$: total social travel costs from road traffic accidents costs (in KRW/day)

$(UTAOR)_{at,rt}$: unit traffic accident occurrence rate by traffic accident type and road type (in person/vehicle-km, or accident numbers/vehicle-km)

$(UTACR)_{at,rt}$: unit road traffic accident cost rate by traffic accident type and road type (in KRW/person, or KRW/accident number)

$Length_l$: length of link l of road networks (in km)

Vol_l : volume on link l of road networks (in vehicles), where links of road networks include all transfer routes within SMRS

AT : traffic accident type (death of person, injury to person, damage to vehicle, damage to non-vehicle)

RT : road type (national expressway, national road, local road (special metropolitan city road/metropolitan city road, provincial road, municipal/county/district road))

L : total links of road networks (including all transfer routes within SMRS)

Pure Accident Cost : all costs regarding damages on people and damages on non-person

Table 5-8. Occurrence of Road Traffic Accidents (2013)

Accidents/10^9 vehicle-km, People/10^9 vehicle-km

Classfication	Damages on People				Damages on Non-Person	
	Death		Injury		Vehicles	Non-Vehicle
	No. of Accident	No. of People	No. of Accident	No. of People	No. of Accident	No. of People
National Expressway	0.52	0.6	5.85	15.76	113.9	77.07
National Highway	2.57	2.72	56.78	105.73	1063.36	716.66
Local Road	2.85	3.02	66.05	110.61	1234.85	833.42

Source: MOLIT (2013)

Table 5-9. Unit Costs of Traffic Accidents on Road Networks (2013)

Unit: 10,000 KRW/Person, 10,000 KRW/Accident)

Classification			Pure Accident Costs	Administration Fee for Police	Administration Fee for Insurance	Subtotal	Costs of PGS	Total
Damages on People	Death (PGS)	No. of People	**41,716 (12,428)**	**98.1**	**76.8**	**41,891**	**12,428.0**	**54,319.0**
	Injury (PGS)	No. of People	**337 (1,450)**	**81.1**	**51.6**	**470**	**1,450.0**	**1,920.0**
Damages on Non-Person	Vehicles	No. of Accident	**122.7**	**5.7**	**8**	**136.4**		**136.4**
	Non-Vehicle	No. of Accident	**135.9**	**5.7**	**8**	**149.6**		**149.6**

PGS: Pain, Grief, and Suffering

* Pure Accident Costs : all costs regarding damages on people and damages on non-person

Source: MOLIT (2013)

5.5 TSTC from Environmental Impact Costs

The next part of total social travel costs is a TSTC from environmental impact costs, represented as $TSTC_{env}$. The framework of $TSTC_{env}$ is very similar to $TSTC_{op}$ from the perspective of relations between costs and speed of the vehicle. The environmental impact from traffic is very broad, such as air pollution, noise, vibration, ecological impact, and so on. The Guidelines of feasibility study of transport facilities chose factors for environmental impact that had major effects and that could be expressed numerically (MOLIT, 2013; KDI, 2016). In this work, only air pollution will be selected to compare environmental impact costs, both in the normal situation and a disrupted situation.

$TSTC_{env}$ is defined in Equation 5-7, the factors of which are mainly determined by speed of vehicles, length of links, and traffic volumes on road networks.

$$TSTC_{env} = \sum_{m=1}^{M}\sum_{l=1}^{L}\left(e_{m0} + e_{m1} \times Speed_{m,l} + e_{m2} \times {Speed_{m,l}}^2 + e_{m3} \times {Speed_{m,l}}^3\right) \times \ Length_l \ \times \ \left(Vol_{m,l}\right) \tag{5-7}$$

where

$TSTC_{env}$	: total social travel costs from environmental costs (in KRW/day)
e_{mi}	: coefficients of environmental impact costs functions by mode *m* (*i* = 0, 1, 2, 3)
$Speed_{m,l}$	: travel speed of transport mode *m* on link *l* of road networks (in hours)
$Length_l$	: length of link *l* of road networks (in km)
$Vol_{m,l}$	: volume of transport mode *m* on link *l* of road networks (in vehicles) where links of road networks include all transfer routes within SMRS
M	: all transport modes for road networks (car, bus with scheduled operation, other bus including chartered bus, taxi, truck)
L	: total links of road networks (including all transfer routes within SMRS)

Table 5-10 and Table 5-11 show unit environmental impact costs by speed and type of vehicle. Components of environmental impact focus on air pollution and are: carbon monoxide, nitrogenous compound, hydrocarbon, particulate matter (PM), and carbon dioxide. Particulate matter is given by urban and rural area in order to reflect those widely different emission rates. The larger the vehicle, the more expensive is its environmental impact costs, similar to its operating costs. It appears that there is an optimal speed which minimises environmental impact costs and these are different for each type of vehicle. This work adopts the same the guideline from the KDI and the MOLIT for the function of total operating cost of each vehicle with speed (MOLIT, 2013; KDI, 2016).

Table 5-10. Unit Environmental Impact Costs – Part 1 (2013)

Unit: KRW/km

Classifi.	Speed	CO	NOx	HC	PM		CO2	Sum	
					Urban	Rural		Urban	Rural
Auto	10	35.5	8.48	8.16	22.55	2.08	60.04	134.72	114.25
	20	22.47	5.23	5.68	17.14	1.58	40.1	90.62	75.06
	30	18.45	3.95	5.03	15.33	1.42	31.67	74.44	60.52
	40	16.52	3.25	4.75	13.53	1.25	26.78	64.84	52.56
	50	15.51	2.81	4.59	12.63	1.17	23.52	59.06	47.59
	60	15.08	2.49	4.5	11.73	1.08	21.15	54.95	44.3
	70	14.75	2.36	4.44	11.73	1.08	20.47	53.74	43.1
	80	14.5	2.39	4.39	10.82	1	20.9	53	43.18
	90	14.31	2.44	4.36	10.82	1	22.11	54.05	44.22
	100	14.14	2.51	4.33	9.92	0.92	24.09	55.01	46
Mini-Bus	10	16.31	17.95	3.37	142.52	13.16	91.43	271.59	142.23
	20	11.09	11.77	2.02	103.73	9.58	60.48	189.09	94.93
	30	8.94	9.2	1.52	86.59	8	47.49	153.74	75.15
	40	7.69	7.72	1.25	76.67	7.08	40	133.34	63.74
	50	6.87	6.74	1.06	69.46	6.41	35.02	119.15	56.1
	60	6.25	6.05	0.93	64.04	5.91	31.41	108.68	50.55
	70	5.78	6.37	0.84	60.44	5.58	30.71	104.14	49.28
	80	5.41	6.82	0.77	56.83	5.25	31.41	101.25	49.67
	90	5.1	7.44	0.71	54.12	5	33.46	100.84	51.72
	100	4.84	8.22	0.66	52.32	4.83	36.86	102.9	55.42
Regular Bus	10	16.13	70.14	8.73	134.4	12.41	191.95	421.36	299.36
	20	10.63	49.1	5.57	110.95	10.24	135.17	311.41	210.71
	30	8.32	39.86	4.28	98.32	9.08	109.14	259.92	170.68
	40	7	34.36	3.55	90.2	8.33	95.22	230.34	148.46
	50	6.12	30.64	3.07	84.79	7.83	87.58	212.2	135.24
	60	5.48	27.9	2.74	81.18	7.5	83.96	201.27	127.58
	70	4.99	25.77	2.48	77.57	7.16	83.49	194.3	123.88
	80	4.61	24.06	2.27	73.97	6.83	86.05	190.96	123.82
	90	4.3	29.06	2.1	72.16	6.66	92.25	199.87	134.37
	100	4.03	41.2	1.96	69.46	6.41	103.78	220.43	157.39
Large Bus	10	74.46	146.92	37.38	244.45	22.57	348.05	851.27	629.39
	20	48.94	112.57	26.67	185.82	17.16	255.46	629.47	460.81
	30	38.57	95.63	21.26	157.86	14.58	207.79	521.11	377.84
	40	32.58	84.67	17.62	141.62	13.08	179.62	456.11	327.56
	50	28.61	76.71	14.89	128.99	11.91	161.85	411.05	293.97
	60	25.74	70.5	12.75	119.97	11.08	150.45	379.41	270.52
	70	23.57	65.49	11.03	113.66	10.49	143.44	357.18	254.01
	80	21.84	61.32	9.61	107.34	9.91	139.8	339.91	242.48
	90	20.42	57.79	8.43	102.83	9.5	139.05	328.53	235.19
	100	19.23	54.74	7.46	98.32	9.08	141.12	320.87	231.63
Light Truck	10	11.25	19.42	2.14	127.19	11.74	86.62	246.62	131.18
	20	7.38	12.4	1.45	87.5	8.08	65.02	173.75	94.33
	30	5.77	9.52	1.15	70.36	6.5	54.98	141.79	77.93
	40	4.84	7.91	0.97	60.44	5.58	48.81	122.98	68.13
	50	4.23	6.84	0.86	54.12	5	44.51	110.56	61.43
	60	3.78	6.09	0.78	48.71	4.5	41.28	100.63	56.42
	70	3.45	6.66	0.71	45.1	4.16	42.39	98.32	57.38
	80	3.17	7.55	0.66	41.49	3.83	45.56	98.44	60.78
	90	2.96	8.22	0.61	38.79	3.58	51.81	102.39	67.18
	100	2.77	8.68	0.58	36.98	3.41	61.14	110.15	76.58

Table 5-11. Unit Environmental Impact Costs – Part 2 (2013)

Unit: KRW/km

Classifi.	Speed	CO	NOx	HC	PM		CO2	Sum	
					Urban	Rural		Urban	Rural
Medium Goods Truck	10	62.14	102.61	30.54	429.37	39.65	189.37	814.02	424.3
	20	39.79	68.46	18.94	306.69	28.32	128.24	562.11	283.74
	30	30.66	54.03	14.32	252.57	23.32	102.55	454.13	224.88
	40	25.48	45.67	11.74	220.1	20.32	89.76	392.75	192.97
	50	22.07	40.1	10.07	197.54	18.24	83.57	353.35	174.05
	60	19.64	36.04	8.87	180.41	16.66	81.78	326.74	162.99
	70	17.78	32.94	7.98	167.78	15.49	83.86	310.33	158.05
	80	16.32	30.48	7.28	156.95	14.49	90.43	301.46	159
	90	15.13	28.45	6.72	148.84	13.74	103.86	302.99	167.9
	100	14.13	26.75	6.24	141.62	13.08	130.99	319.73	191.19
Large Goods Truck	10	84.09	252.03	33.67	731.55	67.55	337.92	1439.25	775.26
	20	59.54	193.6	21.6	535.81	49.48	255.73	1066.28	579.94
	30	48.64	165.92	16.66	446.51	41.23	213.36	891.09	485.81
	40	42.14	148.72	13.86	392.38	36.23	189.09	786.19	430.04
	50	37.71	136.61	12.01	354.5	32.73	174.96	715.79	394.02
	60	34.43	127.46	10.69	326.54	30.15	167.56	666.67	370.29
	70	31.88	120.19	9.68	304.89	28.15	165.41	632.05	355.31
	80	29.83	114.24	8.89	286.85	26.49	168.1	607.91	347.55
	90	28.13	109.23	8.24	272.41	25.15	176.15	594.16	346.9
	100	26.69	104.94	7.71	259.78	23.99	191.18	590.31	354.51

Source: MOLIT (2013)

As a matter of fact, environmental impact measurement has not been comprehensively developed or practiced, even within environmental resource agencies. Many environmental issues are difficult to quantify (AASHTO, 2008). Other countries have their own guidelines for assessing the environmental impact from vehicle emission. The UK government recommended updated vehicle emission curves for use in the National Transport Model. This model was an outcome of the Department for Transport's main strategic policy, in order to forecast traffic levels and the subsequent congestion and emissions impact on the UK national road network. The model provides updated speed-emission factor curves for NO_x, PM_{10}, fuel consumption, and CO_2. For example, the basic model for NO_x emissions from a medium-sized petrol car is an equation of the form $EF = k \times (a+bx+cx^2+dx^3+ex^4+fx^5+gx^6)/x$, in g/km with speed x km/h. Table 5-12 shows the coefficients (Li *et al.*, 2009; Department for Transport, 2016).

Table 5-12. NO_x Emission Model from Medium Car in the UK (2009)

Vehicle Type	Fuel Type	Engine Capacity	Emission Standard	Coefficients								Valid Speed Range	
				a	b	c	d	e	f	g	k	min. (km/h)	max. (km/h)
Car < 2.5t	Petrol	1400cc-2000cc	Pre-Euro1	5.8816	0.6836	0.0139	0	0	0	0	1	5	140
			Euro1	2.3658376	0.1992612	0.0006471	3.22E-06	0	0	0	1	5	120
			Euro2	1.0952615	0.1201239	0.0006135	1.17E-06	8.78E-09	0	0	1	5	140
			Euro3	0.4370444	0.0613598	8.02E-05	8.83E-08	0	0	0	1	5	140
			Euro4	0.5169139	0.0345016	5.49E-05	4.09E-07	0	0	0	1	5	120
			Euro5	0.5169139	0.0345016	5.49E-05	4.09E-07	0	0	0	0.594	5	120
			Euro6	0.5169139	0.0345016	5.49E-05	4.09E-07	0	0	0	0.594	5	120

Source: Li *et al.* (2009), Updated Vehicle Emission Curves for Use in the National Transport Model

Holland (2002) asserted that air pollution costs were dependent on overall levels of pollution, geographic location of emission sources, height of emission source, local and regional population density, meteorology, and so on. He identified different monetary values for SO_2, NO_x, PM2.5, and VOCs (volatile organic compounds) by European country, as seen in Table 5-13.

Table 5-13. Marginal External Costs of Vehicle Emissions (2000 prices)

Classification	SO_2 (€/tonne)	NO_X (€/tonne)	PM2.5 (€/tonne)	VOCs (€/tonne)
Austria	7,200	6,800	14,000	1,400
Belgium	7,900	4,700	22,000	3,000
Denmark	3,300	3,300	5,400	7,200
Finland	970	1,500	1,400	490
France	7,400	8,200	15,000	2,000
Germany	6,100	4,100	16,000	2,800
Greece	4,100	6,000	7,800	930
Ireland	2,600	2,800	4,100	1,300
Italy	5,000	7,100	12,000	2,800
Netherlands	7,000	4,000	18,000	2,400
Portugal	3,000	4,100	5,800	1,500
Spain	3,700	4,700	7,900	880
Sweden	1,700	2,600	1,700	680
UK	4,500	2,600	9,700	1,900
EU-15 Average	5,200	4,200	14,000	2,100

Source: Holland (2002), Estimates of the Marginal External Costs of Air Pollution

5.6 TSTC from Parking Costs

The final term for total social travel costs is a TSTC from parking costs. If the SMRS is disrupted, vehicles on the road networks will increase and more parking spaces are necessary for those vehicles, temporarily or potentially. TSTC from parking costs was originally adopted when benefits from the newly-planned urban railway projects were assessed (KDI, MOLIT).

It is normally assumed that the ownership of cars is not related to the availability or otherwise of railway networks. Therefore, a disruption on the SMRS does not have an impact on parking spaces in residential areas. In addition, trip purposes of cars are limited to trips to work, to school, to business, and for social activities, and this is 57.4% of total car trips. The remaining 42.6% are returning home and can be excluded for calculating the TSTC from parking costs because the parking spaces for those are located at homes. Any given parking service is used an average of 2.34 times a day. Unit operating cost for parking service in urban areas is estimated as 1,740 KRW/parking space. In order not to count car trips twice for one parking space, we define one round trip has a demand for one parking slot in the destination area. Therefore, the total amount of trip distribution should be decreased by half (MOLIT, 2013).

Equation 5-8 represents the TSTC from parking costs. The ½ in the equation means one parking space for one round trip.

$$TSTC_{par} = \frac{1}{2}\sum_{i,j}^{P} T_{ij}^{p} \times \frac{UC_{par}}{f_{par}} \tag{5-8}$$

where

$TSTC_{par}$: total social travel costs from parking costs of cars (in KRW/day)

T_{ij}^{p} : traffic volume from origin *i* to destination *j* with trip purpose *p* (traffic/day)

P : trip purposes that require parking spaces (trips to work, school, business, social activities)

f_{par} : frequency of using parking service (rotation number of parking per day)

UC_{par} : unit cost for parking per day per parking space (in KRW/day/parking space)

5.7 TSTC and Integrated Vulnerability of Transport Networks

Finally, TSTC was defined in Equation 5-1 as the summation of total social travel costs from six aspects: travel time costs, operating costs of road networks and the SMRS, road traffic accidents costs, environmental impact costs, and parking costs. This is repeated in Equation 5-9. Total social travel costs when the SMRS is disrupted is abbreviated as $(\sum TSTC)_{dis}$, while total social travel costs in the normal situation is abbreviated as $(\sum TSTC)_{nor}$. The difference of these two will be regarded as the integrated vulnerability of transport networks, Equation 5-10. The Increasing Rate of the integrated vulnerability is Equation 5-11. The transport axis that produces the highest increasing rate in the whole transport networks, is the weakest one in the SCA.

$$TSTC = \sum TSTC_{t.t} + TSTC_{op.road} + TSTC_{op.SMRS} + TSTC_{t.a} + TSTC_{env} + TSTC_{par} \qquad (5\text{-}9)$$

$$IVTN = \left(\sum TSTC\right)_{dis} - \left(\sum TSTC\right)_{nor} \qquad (5\text{-}10)$$

$$Increasing\ Rate = \frac{(\sum TSTC)_{dis} - (\sum TSTC)_{nor}}{(\sum TSTC)_{nor}} \times 100\ (\%) \qquad (5\text{-}11)$$

where

IVTN : Integrated Vulnerability of Transport Networks (in KRW/day)

$(\sum TSTC)_{dis}$: Total Social Travel Costs in the disrupted situation of the SMRS (in KRW/day)

$(\sum TSTC)_{nor}$: Total Social Travel Costs in the normal situation of the SMRS (in KRW/day)

5.8 Summary

This chapter dealt with how to define the vulnerability of transport networks by adopting the TSTC. This work calculated the TSTC using the costs contributed by the following six sources: travel time costs, operating costs of car travellers, operating costs of the SMRS, road traffic accident costs, environmental impact costs, and parking costs.

TSTC from travel time costs are mainly produced by increase of travel time in road networks when there is a disruptive event on the SMRS. Travellers who want to transfer from the SMRS to their cars are likely to experience more congestion than normal situation. When TSTC from travel time costs are calculated, there are two basic factors: value of travel time, and average number of passengers by each transport mode (KDI, 2016). Travel time and volume per each link of transport networks from the result of trip assignment are multiplied by value of travel time.

Increased traffic on the road networks can also escalate the operating costs of car travellers such as fuel, engine oil, tyre wear, and depreciation. Increased traffic on the road networks can also raise the social costs from the viewpoint of the environment. Because these are largely determined by vehicle speed and type, operating costs and environmental impacts costs are normally defined by the unit cost per vehicle-km, length of links, traffic volumes for each transport mode (Equation 5-3, 5-7). The unit cost per vehicle-km is defined as a cubic function of running speed of transport (MOLIT, 2013).

Operating costs of railway can be projected by diverse models with several variables: personal expenses, costs of power and electricity, maintenance expenses, general management expenses, and alternative investment costs for trains and railway infrastructure. Since Kim *et al.* (2016) modelled accurately the operating costs function on the railway networks in Korea, this thesis adopted the model to calculate the impact of disruptive events on the SMRS. The operating costing function is consisted of five independent variables: average distance between stations, daily train operation distance, total passenger capacity of a train, driving mode (manned/unmanned), and investment type (public/private).

TSTC from road traffic accident costs are approximately estimated on the assumption of the relationship between probability of traffic accident and total volume of the road networks in the SCA. TSTC from parking costs are also calculated principally by the increased volume on the road networks. Coefficients for the accident costs and parking costs are determined statistically (MOLIT, 2013; KDI, 2016).

Chapter 6 Data Collection by Online Survey

In order to assess the vulnerability of transport networks in the SCA, it is necessary to collect travellers' choices in the event of a disruption. Some travellers may have experienced a disruptive event while others have not suffered a failure of the SMRS at all. Travellers' choices in a disruptive situation are scarcely included in statistical data due to the irregularity of the event and diversity of individual choices. Furthermore, location, frequency, duration, and impact of disruptions, cannot be predicted in the real situation. It is therefore difficult determine travellers' intentions through direct observation. A survey stated intentions is required to collect travellers' thoughts in the event of disruptions.

6.1 Online Survey Design

When a disruptive event on the SMRS occurs, personal attitudes are very different to those during normal circumstances. Since normal services of the SMRS are not available any more, travellers need to find alternative transport modes and travel routes. Therefore, it is necessary to identify travellers' choice in a disrupted situation. Since it is rare for travellers to experience an extreme incident, the data revealed does not properly explain travellers' choice in the situation. There have been little data of travellers' modified choices with the partially suspended SMRS because operators of the SMRS have mainly focused on recovery of the disrupted section of the SMRS. Therefore, stated intention survey is required so that the inclination of travellers in an abnormal situation can be analysed. An online survey was thus adopted to collect travellers' imaginary reactions to the disrupted operation of the SMRS.

For the analysis of integrated vulnerability of the SMRS and road networks in the SCA, this thesis supposed that several sections of the SMRS were disrupted for one day according to each six transport axis. For example, in the 1st Incheon transport axis, 17 stations from Incheon station to Onsu station of the SMRS Line 1 were suspended. The disrupted stations were located in Incheon metropolitan city and Bucheon city, not Seoul Metropolitan City. The scenarios of disruptions on the SMRS were designed so that long distance travellers' response to the suspended SMRS could be identified. Details of scenario of disruptions on the SMRS were illustrated in Table 7-1 of section 7.1. This thesis did not consider the causes of disruptive events on the SMRS. Terrorist attacks did not taken into account, either. Actually, it was supposed that there was no security problem although a specific section of the SMRS was not operated. Questionnaire for the participants of online survey explained that a specific section of the SMRS was suspended according to the six transport axes and the questionnaire asked participants' hypothetic intentions or choices.

Section

3.4 Commuting trip in the SCAshowed that commuters' responses to the disrupted SMRS were the same as travellers whose trip purpose was not going to work. Therefore, the online survey focused on commuters rather than overall travellers. Sufficient samples must be obtained to completely cover the commuters' choices in an imaginary situation. Commuters' decisions about what they would like to do to reach work will be revealed by the survey. After analysing inferred demand, travellers will be virtually redistributed to the available transport networks, except the one disrupted line, by revising the O/D data corresponding to different transport modes. They have some alternatives: driving their own cars or using taxis, using the bus with scheduled operation, or another bus for an emergency, and detouring across other subway lines. After comparing overall social travelling costs in both normal and disruptive circumstances, the vulnerability of each SMRS, including adjacent road networks, will be found. TransCAD is the main program used for most of the vulnerability assessment procedures.

Specific inclusion criteria were:

1. Aged over 18
2. Usually take a subway or a train as their main commuting mode
3. A commuter who works in Seoul and lives in Incheon or Gyeonggi Province

To recruit sufficient participants, the researcher contacted various organisations. The Federation of Korean Industries (FKI) is a multifunctional association and consists of Korea's major conglomerates and associated members. The next source for survey participants was the list of companies registered on the Korea Exchange. Most conglomerates or high-potential companies are enrolled in either the Korea Exchange or in Korean Securities Dealers Automated Quotations (KOSDAQ). Another important source for survey population was central government, local government, and other public organisations such as universities, and national museums.

The researcher contacted the personnel department managers of these organisations individually, and asked them to distribute invitation email to their employees. Since this survey was implemented by an online questionnaire, the cooperation of companies or institutions was necessary to allow its employees to access the survey site from the internal office network. When the employer agreed to distribute the invitation card, an email invitation letter was distributed by the employer through their internal office network.

The initial plan was to collect over 400 participants for each transport axis in order to apply a 95% confidence level and 5% error margin for statistical analyses. For the six transport axes, this required more than 2,400 participants. Even though survey assistants were hired to recruit participants at public places such as subway lines or outside restaurants near big organisations, only 200 participants were recruited for some axes. In total, 1,415 participants responded to this online survey over six transport axes. The sample size was based on Cochran's sample size formula for categorical data as follows (Bartlett *et al.*, 2001).

$$n_1 = \frac{t^2 * (p)(q)}{d^2} = \frac{(1.96)^2 * (0.5)(0.5)}{(0.05)^2}$$

= 384, the initial target number of participants

where

t	: value for selected alpha level of 0.025 in each tail = 1.96 (the alpha level of 0.05)
$(p)(q)$	: estimate of variance = 0.25 (standard deviation of 0.5)
d	: acceptable margin of error for proportion being estimated = 0.05

$$n_2 = \frac{(t)^2 * (p)(q)}{(d)^2} = \frac{(1.96)^2 * (0.5)(0.5)}{(0.07)^2}$$

= 196, final target number of participants

where

t	: value for selected alpha level of 0.025 in each tail = 1.96 (the alpha level of 0.05)
$(p)(q)$	: estimate of variance = 0.25 (standard deviation of 0.5)
d	: acceptable margin of error for proportion being estimated = 0.07

This formula states that the acceptable margin of error for this study is 7% with a confidence level of 95%, which means alpha level or significance is 0.05.

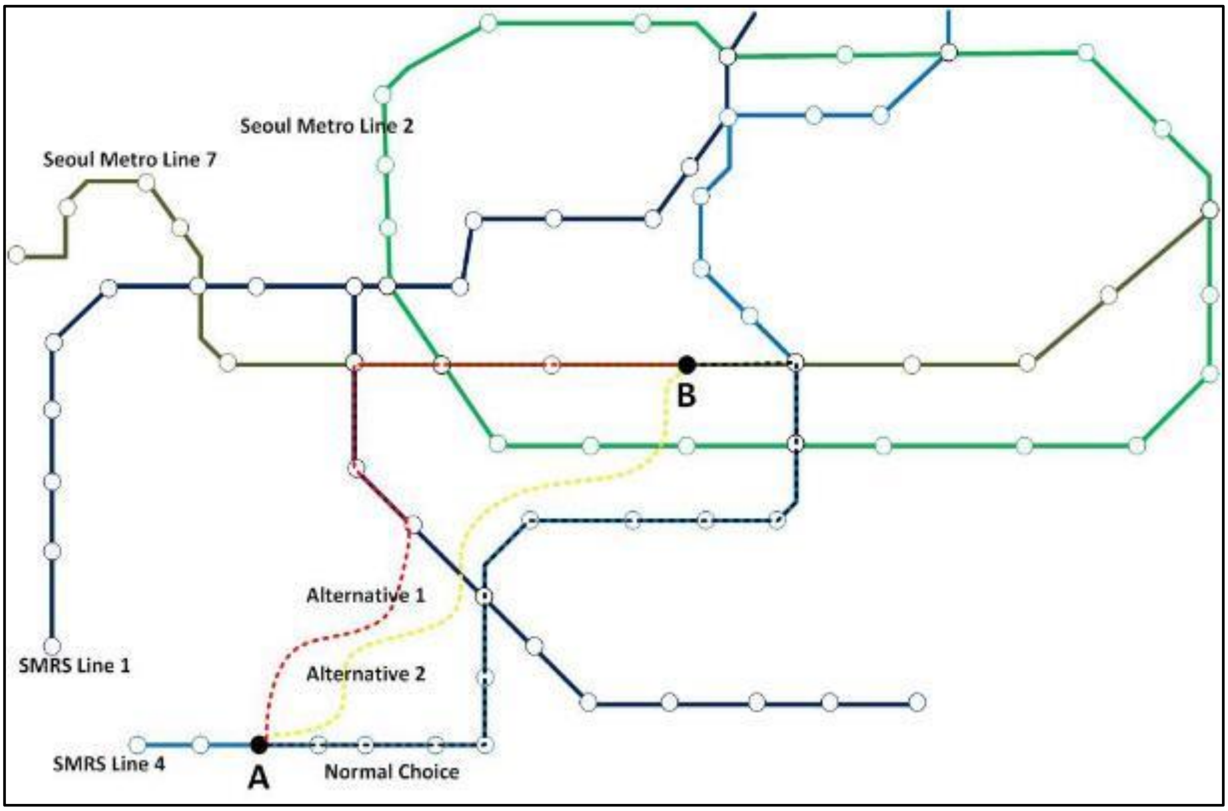
6.2 Structure of Questionnaire

If travellers want to continue their original travel in the event of disruptions on the SMRS, there can be several alternatives: driving their own cars, using taxis, taking buses or utilising other lines of the SMRS by approaching other station with transport modes on road networks. A commuter is a typical example because commuting trips are relatively inelastic to partial malfunction of transport networks.

In Figure 6-1, one imaginary commuter usually goes to work using Lines 4 and 7, joining at station A, and alighting at station B. When their normal mode choice is blocked (Line 4 or station A unavailable), the commuter should choose an alternative because they still want to go to work. A possible substitution is a combination of road networks and the SMRS together as Alternative 1. Another possibility is that the commuter can arrive in their office without boarding any sections of the SMRS as in Alternative 2.

The basic assumption for the online survey is very similar to Figure 6-1. Participants were required to choose among their alternatives because of unavailability of their optimised travel routes on the SMRS.

Figure 6-1. Possible Alternatives of Mode Transfer after Disruption on the SMRS



The survey has three sections: commuting information in normal situations, imaginary or real commuting information in a disrupted SMRS, and participant information and their household. Preliminary qualification questions prefaced these sections.

In the first section, questions were linked with the location of home and workplace, average travel time for going to work, and major travel modes and routes. To get the entire route information, identification of transfer stations of the SMRS was compulsory.

The second section asked about decisions regarding transport mode choices, assuming a disruption had occurred, and an increase or decrease of travel time that followed. Also required was how the participant would get information about the disrupted SMRS operations. The actual choices were probed where respondents had experienced the same situation as the assumption. Questions were almost the same as those of the hypothetical situation. Another part of this section concerned the duration of disruptive events on the SMRS. In order to find the critical duration of malfunction before the commuter changed to an alternative transport mode, four questions were allocated.

The last section was demographic information such as gender and age, as well as the economic background of the household. This is used to relate stated intention during disruptions to their socio-economic characteristics.

6.3 Online Survey Platform

The online survey was executed using the i-Survey[11] tool from 11 April to 15 November 2016, about 7 months. The ID of the i-Survey was 19558. Before the i-Survey was launched, the plan as approved by the Ethics Committee of the University of Southampton through ERGO[12]. Approved Ethics Committee Number was 19475.

[11] i-Survey is a survey generation and research tool of the University of Southampton for distributing online questionnaires. It is free to researchers at the University of Southampton.

[12] ERGO, Ethics and Research Governance Online, is an electronic document handling system of the University of Southampton for Ethics forms, IRGA forms and any other supporting documentation relevant to research.

6.4 Alternative Mode Shares

Table 6-1 summarises the final result of the survey, not distinguishing the six transport axes. The survey had 1,415 respondents. It is supposed that 1,415 respondents' transport mode in a normal situation is the Seoul Metropolitan Railway Systems (SMRS).

The left side of Table 6-1 is the original result of the survey and demonstrates the proportions of each mode transfer from the SMRS due to some disruption, without considering transport axis. 331 respondents selected car as their substitutive mode and 54 people chose bus supported by car. 59 participants picked up taxi as an alternative while 98 respondents chose bus assisted by taxi. 457 people preferred bus to other transport modes. People who wanted to use other lines of the SMRS continuously totalled 402 (37+31+307+27).

Table 6-1. Alternative Mode Shares of All Participants

Alternative Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	331	23.4%		Car	385	27.2%
Taxi	59	4.2%		Taxi	157	11.1%
Bus	457	32.3%		Bus	457	32.3%
Car+Bus	54	3.8%		O.SMRS	402	28.4%
Taxi+Bus	98	6.9%		W.Home	8	0.6%
Car+Other Line of SMRS	37	2.6%		Bike+Walk	6	0.4%
Taxi+Other Line of SMRS	31	2.2%		Sum	1,415	100.0%
Bus+Other Line of SMRS	307	21.7%				
Taxi+Bus+Other Line of SM	27	1.9%				
Working at Home	8	0.6%				
Bike+Walk	6	0.4%				
Sum	1,415	100.0%				

The right side of Table 6-1 was converted by summing the data of mode transfer from the left side. The choice of car was added to the choice of bus supported by car (331+54), and the choice of taxi was added to the choice of bus assisted by taxi (59+98). However, the proportion of bus usage remained at its original value (32%) because of our basic assumption that pure bus demand would be solved with newly-injected buses, like chartered buses, while bus demand related to other

transport modes would be accepted within the existing bus services. The suitability of these assumptions was discussed in section

4.5 Assumptions for Analysis.

As a result, 27.2% of all participants, or 385 participants, chose car as their alternative transport mode. 11.1% of all respondents preferred to use a taxi in an emergency situation during trips. Bus was the favourite transport mode for travellers when they could not use the SMRS normally. 457 participants, 32.3%, stated that they would take a bus as a substitute of the partially suspended SMRS. Other available SMRS lines were selected as the second dominant transport mode, noted by 402 participants or 28.4%. The who decided to work at home or bike/walk were 0.6% and 0.4% respectively. In other words, the effect of working at home could be not taken into account when alternative mode shares were analysed.

The result of alternative mode shares from all participants, ignoring each transport axis, gave the average alternative mode shares in the SCA. Different alternative mode shares ratios by transport axis are illustrated in the following tables. The detailed online survey data of the six transport axes are given in Appendix 2.

Table 6-2. Alternative Mode Shares in the Six Transport Axes

1st Incheon Axis				2nd Suwon Axis		
Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	82	32.2%		Car	83	25.5%
Taxi	31	12.2%		Taxi	39	12.0%
Bus	65	25.5%		Bus	109	33.4%
O.SMRS	72	28.2%		O.SMRS	92	28.2%
W.Home	3	1.2%		W.Home	1	0.3%
Bike+Walk	2	0.8%		Bike+Walk	2	0.6%
Sum	255	100.0%		Sum	326	100.0%
3rd Seongnam Axis				**4th Namyangju Axis**		
Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	69	30.8%		Car	47	23.5%
Taxi	23	10.3%		Taxi	31	15.5%
Bus	82	36.6%		Bus	61	30.5%
O.SMRS	48	21.4%		O.SMRS	59	29.5%
W.Home	2	0.9%		W.Home	1	0.5%
Bike+Walk	-	0.0%		Bike+Walk	1	0.5%
Sum	224	100.0%		Sum	200	100.0%
5th Uijeongbu Axis				**6th Goyang Axis**		
Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	41	20.1%		Car	63	30.6%
Taxi	17	8.3%		Taxi	16	7.8%
Bus	60	29.4%		Bus	80	38.8%
O.SMRS	85	41.7%		O.SMRS	46	22.3%
W.Home	1	0.5%		W.Home	-	0.0%
Bike+Walk	-	0.0%		Bike+Walk	1	0.5%
Sum	204	100.0%		Sum	206	100.0%

Table 6-2 shows the alternative mode shares in the six transport axes. The first thing to be identified was that there are statistically significant differences of alternative mode choices by transport axis. When there is a disruptive event on the SMRS, the most critical mode change is from the SMRS to car because TSTC are strongly related to the number of cars on the road. In other words, it is important to identify differences of the proportion of cars as an alternative mode on the six transport axes.

Assuming that different transport axes represent different populations, the proportion of car choices between two different transport axes need to be compared. Since there are six transport axes, that is 15 combinations.

Table 6-3 summarises the ratio of cars as alternative mode by transport axis. 1st Incheon axis experienced the highest proportion, equivalent to 0.32, and 3rd Seongnam axis and 6th Goyang axis also showed relatively high proportion of cars. By contrast, 5th Uijeongbu axis recorded the lowest proportion with 0.20 and 4th Namyangju axis and 2nd Suwon axis were categorised as low proportion of cars. However, proportion itself is not sufficient to assess whether there are significant differences between different transport axes. Therefore, Table 6-4 shows the *p*-values from a 2-sample test for equality of proportions using R, which is a comprehensive statistical analysis program.

Table 6-3. Proportion of Cars as Alternative Mode in the Six Transport Axes

Transport Axis	Participant numbers		Proportion
	Car	Total	
1st Incheon	82	255	32.2%
2nd Suwon	83	326	25.5%
3rd Seongnam	69	224	30.8%
4th Namyangju	47	200	23.5%
5th Uijeongbu	41	204	20.1%
6th Goyang	63	206	30.6%

p-value means the minimum significance level that allows rejection of the null hypothesis and adoption of the alternative hypothesis. Generally speaking, the null hypothesis assumes that there is no difference between the samples. Thus, if the *p*-value is less than a given significance level, the null hypothesis can be rejected and there is a significant difference between the two selected transport axes (Washington *et al.*, 2010).

Table 6-4 gives *p*-values for the 15 combinations of the six transport axes, ranging from 0.0052 to 1.0000. If the significance level is chosen as 0.05 or 5%, it seems that there are significant differences for the proportion of cars between 1st Incheon axis and 5th Uijeongbu axis, the 3rd Seongnam axis and 5th Uijeongbu axis, and the 5th Uijeongbu axis and 6th Goyang axis. Consequently, it is plausible to conclude that passengers of the SMRS from 1st Incheon axis, 3rd Seongnam axis, and 6th Goyang axis chose cars as their alternative mode more often than other transport axes. Additionally, the 5th Uijeongbu axis experienced quite low transfers from the SMRS to cars when there is a disruptive event.

Table 6-4. *p*-value from 2-Sample Test for Equality of Proportions

Axis	1st	2nd	3rd	4th	5th	6th
1st	-	0.092	0.826	0.054	0.005	0.794
2nd	0.092	-	0.201	0.688	0.189	0.234

3rd	0.826	0.201	-	0.115	0.016	1.000
4th	0.054	0.688	0.115	-	0.479	0.135
5th	0.005	0.189	0.016	0.479	-	0.020
6th	0.794	0.234	1.000	0.135	0.020	-

Table 6-5 compares the alternative mode shares overall result with those of the 1st Incheon axis. 82 respondents chose car as their alternative mode, some 32.2% of the 255 participants. Proportions of taxi, bus, and other SMRS were 12.2%, 25.5%, and 28.2% respectively. The proportions of car were the highest while the proportions of bus were lowest compared with the result of all participants from the entire SCA and the other five transport axes,

Table 6-5. Alternative Mode Shares in the SCA (left) and in 1st Incheon Axis (right)

Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	385	27.2%		Car	82	32.2%
Taxi	157	11.1%		Taxi	31	12.2%
Bus	457	32.3%		Bus	65	25.5%
O.SMRS	402	28.4%		O.SMRS	72	28.2%
W.Home	8	0.6%		W.Home	3	1.2%
Bike+Walk	6	0.4%		Bike+Walk	2	0.8%
Sum	1,415	100.0%		Sum	255	100.0%

Table 6-6 shows similar findings for the 2nd Suwon axis. 83 respondents chose car as their alternative mode, some 25.5% of the 326 participants, the largest response among the six transport axes. Proportions of taxi, bus, and other SMRS were 12.0%, 33.4%, and 28.2% respectively. The ratio for car was quite low while the ratio for bus was relatively high compared with the result of all participants.

Table 6-6. Alternative Mode Shares in the SCA (left) and in 2nd Suwon Axis (right)

Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	385	27.2%		Car	83	25.5%
Taxi	157	11.1%		Taxi	39	12.0%
Bus	457	32.3%		Bus	109	33.4%
O.SMRS	402	28.4%		O.SMRS	92	28.2%
W.Home	8	0.6%		W.Home	1	0.3%
Bike+Walk	6	0.4%		Bike+Walk	2	0.6%
Sum	1,415	100.0%		Sum	326	100.0%

Table 6-7 shows the findings for the 3rd Seongnam transport axis. Compared to the result of all participants from the entire SCA and the other five transport axes, the use of the bus was considerably higher at 36.6% of the 224 participants. The use of cars was also quite high at 30.8%. It appears that road networks in this axis are more convenient than other areas in the SCA. In contrast, the ratio of other SMRS lines was 21.4%, which ranked as the lowest the transport axes.

Table 6-7. Alternative Mode Shares in the SCA (left) and in 3rd Seongnam Axis (right)

Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	385	27.2%		Car	69	30.8%
Taxi	157	11.1%		Taxi	23	10.3%
Bus	457	32.3%		Bus	82	36.6%
O.SMRS	402	28.4%		O.SMRS	48	21.4%
W.Home	8	0.6%		W.Home	2	0.9%
Bike+Walk	6	0.4%		Bike+Walk	-	0.0%
Sum	1,415	100.0%		Sum	224	100.0%

Table 6-8. Alternative Mode Shares in the SCA (left) and in 4th Namyangju Axis (right)

Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	385	27.2%		Car	47	23.5%
Taxi	157	11.1%		Taxi	31	15.5%
Bus	457	32.3%		Bus	61	30.5%
O.SMRS	402	28.4%		O.SMRS	59	29.5%
W.Home	8	0.6%		W.Home	1	0.5%
Bike+Walk	6	0.4%		Bike+Walk	1	0.5%
Sum	1,415	100.0%		Sum	200	100.0%

Table 6-8 shows results for the 4th Namyangju axis by 200 participants. The ratio of taxi usage was 15.5%, the highest of all axes and the whole SCA. The ratio of other SMRS lines was 29.5%, also considerably higher than other transport axes. On the other hand, the ratio for cars was 23.5%, quite low among the six transport axes.

Table 6-9 shows results for the 5th Uijeongbu transport axis. Participants who chose car as their alternative mode were 20.1% of the 204 contributors. This was the lowest ration among the six transport axes. By contrast, the ratio of other SMRS was 41.7%, the highest of all axes.

Table 6-9. Alternative Mode Shares in the SCA (left) and in 5th Uijeongbu Axis (right)

Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	385	27.2%		Car	41	20.1%
Taxi	157	11.1%		Taxi	17	8.3%
Bus	457	32.3%		Bus	60	29.4%
O.SMRS	402	28.4%		O.SMRS	85	41.7%
W.Home	8	0.6%		W.Home	1	0.5%
Bike+Walk	6	0.4%		Bike+Walk	-	0.0%
Sum	1,415	100.0%		Sum	204	100.0%

Finally, Table 6-10 gives the results for the 6th Goyang transport axis. Respondents who chose taxi for a disrupted situation were 7.8% of the 206 participants, the lowest in the whole SCA. However, the most remarkable figure is the ratio of bus at 38.8%. Moreover, the ratio of car usage was quite high at 30.6%. Thus, compared to all participants from the entire SCA, the ratio of other SMRS was much lower, at 22.3%.

Table 6-10. Alternative Mode Shares in the SCA (left) and in 6th Goyang Axis (right)

Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	385	27.2%		Car	63	30.6%
Taxi	157	11.1%		Taxi	16	7.8%
Bus	457	32.3%		Bus	80	38.8%
O.SMRS	402	28.4%		O.SMRS	46	22.3%
W.Home	8	0.6%		W.Home	-	0.0%
Bike+Walk	6	0.4%		Bike+Walk	1	0.5%
Sum	1,415	100.0%		Sum	206	100.0%

6.5 Key Findings except Alternative Transport Modes

The previous section illustrated mainly alternative mode shares in the six transport axes, assuming that a disrupted event occurred on the SMRS where a specific part was suspended for a day. This section covers other important results from the online survey such as how to get information on disruptions, how many travellers have experienced a disruptive event on the SMRS, influence of the duration of disruptive events, and different intentions on alternative modes.

6.5.1 How to get Information on Disruptions

In an ideal situation there is no disruption to the SMRS, and travellers can use all the lines whenever they want to. However, in the real world disruptive events can happen due to intentional attacks, natural disasters, human factors, and maintenance problems. Therefore, it is important for travellers to be aware of the fact that a disruptive event has occurred on a specific section of the SMRS. Information delivery is one of the crucial elements that can help minimise the impact of a disruptive event, by enabling travellers to choose an alternative mode (Blum *et al.*, 2014; Ishida *et al.*, 2014).

Table 6-11 summarises the online survey, regarding information sources that travellers want to use when there is an abnormal situation on the SMRS.

Table 6-11. Where do Travellers Want to Get Information about a Disruption?

Sources	All	1st	2nd	3rd	4th	5th	6th
Mass Media	28.3%	30.6%	25.9%	29.6%	27.2%	28.7%	28.5%
Internet	34.1%	34.6%	33.1%	36.5%	35.7%	32.2%	33.2%
Social Networks	11.0%	9.3%	13.6%	11.0%	9.5%	10.1%	11.3%
Notice from Company	6.9%	7.7%	7.5%	5.8%	6.3%	6.0%	7.7%
Notice from Government	19.7%	17.8%	19.9%	17.1%	21.3%	22.9%	19.3%

The first data column stands for the result of all participants from the SCA. The other columns refer to the six transport axes. Each participant of the online survey was allowed to select two favourite sources.

The most popular source for information on disruptive events was the Internet, with scores from 32.2% to 36.5%. The probable reason for this is the high usage of smart phones, possessed by 83.2% of all South Koreans in 2015 (see Table 4-8). Mass Media ranked second, with 28.3% on average. However, Social Networks and Notice from Company were not much preferred to other sources. In contrast, about one fifth of travellers expected the Government to notify them of disruptive events.

Table 6-12. Where do Travellers Want to Get Information about a Disruption? Mass Media

Axis	1st	2nd	3rd	4th	5th	6th
1st	-	0.123	0.808	0.336	0.604	0.563
2nd	0.123	-	0.260	0.712	0.380	0.428
3rd	0.808	0.260	-	0.542	0.861	0.812
4th	0.336	0.712	0.542	-	0.711	0.765
5th	0.604	0.380	0.861	0.711	-	1.000
6th	0.563	0.428	0.812	0.765	1.000	-

Table 6-13. Where do Travellers Want to Get Information about a Disruption? Internet

Axis	1st	2nd	3rd	4th	5th	6th
1st	-	0.675	0.633	0.800	0.524	0.745
2nd	0.675	-	0.329	0.458	0.839	1.000
3rd	0.633	0.329	-	0.889	0.251	0.400
4th	0.800	0.458	0.889	-	0.352	0.531
5th	0.524	0.839	0.251	0.352	-	0.825
6th	0.745	1.000	0.400	0.531	0.825	-

Table 6-14. Where do Travellers Want to Get Information about a Disruption? Social Networks

Axis	1st	2nd	3rd	4th	5th	6th
1st	-	0.051	0.501	1.000	0.813	0.414
2nd	0.051	-	0.302	0.080	0.124	0.361
3rd	0.501	0.302	-	0.582	0.750	0.991
4th	1.000	0.080	0.582	-	0.898	0.492
5th	0.813	0.124	0.750	0.898	-	0.648
6th	0.414	0.361	0.991	0.492	0.648	-

Table 6-15. Where do Travellers Want to Get Information about a Disruption? Notice from Company

Axis	1st	2nd	3rd	4th	5th	6th
1st	-	1.000	0.359	0.513	0.421	1.000
2nd	1.000	-	0.379	0.546	0.447	1.000
3rd	0.359	0.379	-	0.914	1.000	0.391
4th	0.513	0.546	0.914	-	1.000	0.549
5th	0.421	0.447	1.000	1.000	-	0.457
6th	1.000	1.000	0.391	0.549	0.457	-

Table 6-16. Where do Travellers Want to Get Information about a Disruption? Notice form Government

Axis	1st	2nd	3rd	4th	5th	6th
1st	-	0.456	0.890	0.249	0.079	0.646
2nd	0.456	-	0.346	0.667	0.290	0.890
3rd	0.890	0.346	-	0.187	0.058	0.511
4th	0.249	0.667	0.187	-	0.640	0.558
5th	0.079	0.290	0.058	0.640	-	0.246
6th	0.646	0.890	0.511	0.558	0.246	-

Table 6-17 shows the information sources that travellers actually used in real situations. In this case, people were more dependent on the Internet and Mass Media than in the theoretical situation. Notice from both Company and Government were much lower than stated desires. For example, although 19.7% of travellers wanted Notice from Government, only 8.6% had experienced this. The Social Networks scores were similar in both situations. The gap between travellers' expectations and delivery from each source should be considered when devising strategies for more resilient transport networks in the SCA.

Table 6-17. Where Did Travellers Get Information about a Real Disruption?

Sources	all	1st	2nd	3rd	4th	5th	6th
Mass Media	30.0%	41.1%	35.0%	23.6%	34.3%	22.2%	20.5%
Internet	47.7%	46.6%	46.0%	65.5%	43.3%	44.4%	45.2%
Social Networks	10.9%	4.1%	12.0%	10.9%	11.9%	9.7%	16.4%
Notice from Company	2.7%	2.7%	2.0%	0.0%	1.5%	2.8%	6.8%
Notice from Government	8.6%	5.5%	5.0%	0.0%	9.0%	20.8%	11.0%

6.5.2 How Many Travellers Had Experienced Disruptions?

Table 6-18 summarises the ratios of travellers who had experienced any disruptive events on the SMRS. On average, 32.7% of all respondents had experienced disruptions, while 67.3% had not. These ratios did not vary much by transport axis except in one case. Only 25.9% of travellers from the 3rd Seongnam axis had experienced a disruptive event. Since the probability of a disruptive event is not taken into account here, and the impact of an assumed disruption is regarded as the vulnerability of transport networks, we cannot conclude that the 3rd Seongnam axis is the least vulnerable transport axis.

Table 6-18. Those Experiencing Any Disruptive Event on the SMRS

Any Experience?	all	1st	2nd	3rd	4th	5th	6th
Yes	32.7%	32.2%	32.7%	25.9%	34.7%	36.0%	35.4%
No	67.3%	67.8%	67.3%	74.1%	65.3%	64.0%	64.6%

6.5.3 Influence of the Duration of Disruptive Events

When a section of the SMRS is not available, alternative modes can be chosen from road networks or from other parts of the SMRS that are still in normal operation. The road networks may be utilised by private car, taxi, scheduled bus, or temporarily operated bus. Travel time and travel cost vary in line with alternative modes. In addition, alternative modes can differ, dependent on the duration of the disruptive event, because elasticity of travel cost may change with the length of the irregular travelling.

Table 6-19 shows a stated intention of changing alternative modes when a disruptive event continues for longer than one day. On average, 62.6% of travellers said they would alter their alternative transport mode while 37.4% would adhere to their first chosen mode. The 3rd Seongnam axis experienced high positive responses compared with the 1st Incheon axis where there was a lower likelihood of changing modes.

Table 6-19. Changing Modes Because of Long Duration of Disruption

Change Modes?	all	1st	2nd	3rd	4th	5th	6th
Yes	62.6%	57.3%	61.8%	71.9%	65.3%	58.9%	61.2%
No	37.4%	42.7%	38.2%	28.1%	34.7%	41.1%	38.8%

Table 6-20 shows the effect of extended disruptive events on travellers' choice of alternative modes. It seems that 174 participants, who chose one day, misunderstood the question. In the survey scenario, it was assumed that a specific section of the SMRS on each transport axis was suspended for one day. After excluding these 174 participants, 245 participants stated that they would change alternative modes within three days. 115 participants chose a period of between four days and seven days. Another 135 participants would move to a different transport mode when disruptive events continued for longer.

Table 6-20. Duration of Disruptive Event Before Changing to Alternative Modes

	sum	1 day	2 days	3 days				
1~3 days	**419**	**174**	**12**	**233**				
	sum	4 days	5 days	6 days	7 days			
4~7 days	**115**	**37**	**53**	**14**	**11**			
	sum	8 days	9 days	10 days	11 days	12 days	13 days	14 days
8~14 days	**135**	**113**	**10**	**0**	**12**	**0**	**0**	**0**
	sum							
over 15 days	**0**							

What is the criterion that each traveller puts first when disruptive events on the SMRS continue for longer than a day? Table 6-21 shows travellers' preferences in choosing alternative modes. Half of travellers are most sensitive to total travel time when they have to choose among different modes, although there were some differences among the six transport axes. Only 45.1% of travellers in the 2nd Suwon axis selected total travel time as their dominant standard compared with 62.0% of commuters in the 4th Namyangju axis. Since this survey involved commuters residing in Incheon Metropolitan City and Gyeonggi Province with Seoul Metropolitan City as their workplace, it seems reasonable that total travel time was first choice. Total monetary cost came second in the same situation. Reliability of travel time and comfort during unusual travelling were less important.

Table 6-21. Criteria to Change Alternative Modes Because of Long Duration Disruption

Criteria to Change Modes	all	1st	2nd	3rd	4th	5th	6th
Total Travel Time	**50.9%**	**48.2%**	**45.1%**	**50.9%**	**62.0%**	**53.7%**	**50.4%**
Total Monetary Cost	**26.1%**	**28.2%**	**31.7%**	**23.9%**	**20.9%**	**21.1%**	**26.0%**
Reliability of Travel Time	**15.3%**	**16.5%**	**15.6%**	**14.5%**	**12.4%**	**18.7%**	**13.7%**
Comfort during Travel	**6.4%**	**5.9%**	**6.3%**	**8.8%**	**3.9%**	**4.9%**	**8.4%**
Others	**1.4%**	**1.2%**	**1.3%**	**1.9%**	**0.8%**	**1.6%**	**1.5%**
Sum	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

6.5.4 Different Intentions on Alternative Modes

This section explores the relationships between alternative mode shares and major socio-economic characteristics such as age, monthly income, and workplace arrival time.

The relationship between age and alternative mode shares are shown in Table 6-22. The younger generation, in their 20s and 30s, demonstrated high dependency on public transport with car choice considerably lower. Other SMRS lines were selected by up to 39.3% of those in their 20s, but car was chosen by 10.5%. In contrast, 21.6% of the 40s age group determined to use other SMRS lines while 38.2% preferred car as their major alternative modes. 33.3% of travellers at the age of 50s preferred car rather than other transport modes. 36.8% of travellers older than 60 wants to use their cars when there is a disruptive event on the SMRS. This suggests that the younger generation has difficulty affording cars as their main transport mode in both an abnormal and normal situation. Conversely, older age groups are more affluent when it comes to using private cars as their commuting tool. It can be alleged that the age groups older than 40 do not have difficulty to afford their own cars in order to respond to the disrupted SMRS. In other words, age is highly related to the income of each household.

Table 6-22. Alternative Mode Shares by Age

Age: 18~29				**Age: 30~39**		
Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	30	10.5%		Car	153	26.7%
Taxi	35	12.3%		Taxi	59	10.3%
Bus	101	35.4%		Bus	205	35.8%
O.SMRS	112	39.3%		O.SMRS	153	26.7%
W.Home	5	1.8%		W.Home	1	0.2%
Bike+Walk	2	0.7%		Bike+Walk	1	0.2%
Sum	285	100.0%		Sum	572	100.0%
Age: 40~49				**Age: 50~59**		
Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	147	38.2%		Car	40	33.3%
Taxi	50	13.0%		Taxi	10	8.3%
Bus	101	26.2%		Bus	28	23.3%
O.SMRS	83	21.6%		O.SMRS	41	34.2%
W.Home	2	0.5%		W.Home	-	0.0%
Bike+Walk	2	0.5%		Bike+Walk	1	0.8%
Sum	385	100.0%		Sum	120	100.0%
Age: 60+				**Age: all**		
Alter. Mode	Responses	Ratio		Alter. Mode	Responses	Ratio
Car	7	36.8%		Car	377	27.3%
Taxi	-	0.0%		Taxi	154	11.2%
Bus	6	31.6%		Bus	441	31.9%
O.SMRS	6	31.6%		O.SMRS	395	28.6%
W.Home	-	0.0%		W.Home	8	0.6%
Bike+Walk	-	0.0%		Bike+Walk	6	0.4%
Sum	19	100.0%		Sum	1,381	100.0%

Table 6-23 illustrates alternative mode shares by monthly income. Households with lower incomes are less able to use a car as their alternative mode. Although the average ratio for car was 27.3%, in households with a monthly income less than 2 million KRW, only 8.0% of respondents chose car. By contrast, the ratios of bus or other SMRS for the low-income household were considerably higher compared to high-income households. 22.5% of the income group between 2-3 million KRW stated that they would like to use car for commuting in an emergency situation. However, for monthly income more than 3 million KRW, there were no significant differences among income groups, regarding choice of alternative transport modes.

Table 6-23. Alternative Mode Shares by Monthly Income, in KRW

Income: ~2 mil.			Income: 2~3 mil.			Income: 3~4 mil.		
Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Car	4	8.0%	Car	39	22.5%	Car	66	29.2%
Taxi	6	12.0%	Taxi	21	12.1%	Taxi	17	7.5%
Bus	19	38.0%	Bus	51	29.5%	Bus	80	35.4%
O.SMRS	20	40.0%	O.SMRS	60	34.7%	O.SMRS	60	26.5%
W.Home	1	2.0%	W.Home	1	0.6%	W.Home	2	0.9%
Bike+Walk	-	0.0%	Bike+Walk	1	0.6%	Bike+Walk	1	0.4%
Sum	50	100.0%	Sum	173	100.0%	Sum	226	100.0%
Income: 4~5 mil.			**Income: 5~6 mil.**			**Income: 6~7 mil.**		
Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Car	82	26.7%	Car	89	31.3%	Car	43	28.1%
Taxi	40	13.0%	Taxi	37	13.0%	Taxi	9	5.9%
Bus	85	27.7%	Bus	89	31.3%	Bus	54	35.3%
O.SMRS	98	31.9%	O.SMRS	64	22.5%	O.SMRS	47	30.7%
W.Home	1	0.3%	W.Home	3	1.1%	W.Home	-	0.0%
Bike+Walk	1	0.3%	Bike+Walk	2	0.7%	Bike+Walk	-	0.0%
Sum	307	100.0%	Sum	284	100.0%	Sum	153	100.0%
Income: 7 mil. +			**Income: all**					
Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio			
Car	54	28.9%	Car	377	27.3%			
Taxi	23	12.3%	Taxi	153	11.1%			
Bus	64	34.2%	Bus	442	32.0%			
O.SMRS	45	24.1%	O.SMRS	394	28.6%			
W.Home	-	0.0%	W.Home	8	0.6%			
Bike+Walk	1	0.5%	Bike+Walk	6	0.4%			
Sum	187	100.0%	Sum	1,380	100.0%			

* 1GBP ≒ 1,400 KRW, 1mil. KRW ≒ 714 GBP

Lastly, Table 6-24 represents how alternative mode share ratios change with work hours. Sub-tables for arrival times between midnight at 9 am suggest that travellers in the early morning had greater possibility of using a car during a disruption. The ratio of car as alternative mode decreased from 33.3% before 7 am to 24.2% before 9 am. However, commuters who can arrive in workplace after 9 am showed less preference of car and high dependency on public transport like bus and other SMRS lines.

Table 6-24. Alternative Mode Shares by Workplace Arrival Time

Arrival Time: 00.00~06.59			Arrival Time: 07.00~07.59			Arrival Time: 08.00~08.59		
Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Car	38	33.3%	Car	172	32.2%	Car	142	24.2%
Taxi	17	14.9%	Taxi	58	10.9%	Taxi	64	10.9%
Bus	28	24.6%	Bus	164	30.7%	Bus	197	33.6%
O.SMRS	29	25.4%	O.SMRS	135	25.3%	O.SMRS	178	30.4%
W.Home	-	0.0%	W.Home	3	0.6%	W.Home	4	0.7%
Bike+Walk	2	1.8%	Bike+Walk	2	0.4%	Bike+Walk	1	0.2%
Sum	114	100.0%	Sum	534	100.0%	Sum	586	100.0%

Arrival Time: 09.00~09.59			Arrival Time: 10.00~11.59			Arrival Time: 12.00~16.59		
Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Car	18	16.5%	Car	3	13.6%	Car	2	16.7%
Taxi	12	11.0%	Taxi	-	0.0%	Taxi	2	16.7%
Bus	39	35.8%	Bus	10	45.5%	Bus	5	41.7%
O.SMRS	38	34.9%	O.SMRS	9	40.9%	O.SMRS	3	25.0%
W.Home	1	0.9%	W.Home	-	0.0%	W.Home	-	0.0%
Bike+Walk	1	0.9%	Bike+Walk	-	0.0%	Bike+Walk	-	0.0%
Sum	109	100.0%	Sum	22	100.0%	Sum	12	100.0%

Arrival Time: 17.00~20.59			Arrival Time: 21.00~23.59			Arrival Time: 00.00~23.59		
Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Car	-	0.0%	Car	1	100.0%	Car	376	27.2%
Taxi	-	0.0%	Taxi	-	0.0%	Taxi	153	11.1%
Bus	-	0.0%	Bus	-	0.0%	Bus	443	32.1%
O.SMRS	3	100.0%	O.SMRS	-	0.0%	O.SMRS	395	28.6%
W.Home	-	0.0%	W.Home	-	0.0%	W.Home	8	0.6%
Bike+Walk	-	0.0%	Bike+Walk	-	0.0%	Bike+Walk	6	0.4%
Sum	3	100.0%	Sum	1	100.0%	Sum	1,381	100.0%

6.6 Summary

This chapter firstly established the design and the questionnaire structure of the online survey. It then covered the recruitment of the participants for the survey. This thesis supposed that several sections of the SMRS were disrupted for one day according to each six transport axis. The scenarios of disruptions on the SMRS were designed so that long distance travellers' response to the suspended SMRS could be identified. The main question focuses on commuters' mode choice and route selection when they are exposed to malfunctions of their normal commuting mode and route. The survey will also include a question about when that happens and respondents change their alternative modes. Another important question is about effective ways for system managers to deliver disruptive information to commuters. Commuters' individual and socio-economic characteristics are basic questions to understand the background of their choices.

The result of the online survey regarding alternative modes shares was then addressed and analysed. This showed that 32% of the 1,415 respondents preferred to use the bus as an alternative transport mode during a malfunction of the SMRS. 28.4% of total respondents said they would like to use other available SMRS lines and 27.2% of them revealed their intention to drive cars. However, when divided into the six transport axes in the SCA, the preferences for alternative transport modes were different according to each transport axis. The people who decided to work at home or bike/walk were 0.6% and 0.4% respectively. Therefore, the effect of working at home could be not taken into account when alternative mode shares were analysed.

The last part of the chapter dealt with other important results from the survey such as how to get information about disruptions, the number of travellers who had experienced disruptions, the influence of duration of disruptive events, and different intentions on alternative modes according to sundry variables. The most popular source for information on disruptive events was the Internet, with scores 34.1%, probably caused by the high usage of smart phones, possessed by 83.2% of all South Koreans (KISDI, 2015). Mass Media ranked second, with 28.3% on average. When it comes to experience of disruptive events, 32.7% of all respondents had experienced disruptions, while 67.3% had not. In addition, half of travellers are most sensitive to total travel time when they have to choose among different modes. The relationships between alternative mode shares and major socio-economic characteristics such as age, monthly income, and workplace arrival time were also reviewed as a result of online survey.

Chapter 7 Integrated Vulnerability Assessment of Transport Networks

In Chapter 5, the integrated vulnerability assessment of transport networks was defined with the concept of TSTC. In this chapter, after details of the disrupted SMRS are outlined in order to limit the analysis, a specific process of TransCAD analysis is followed. During the process, changing the O/D matrix according to travellers' stated choice during malfunction of the SMRS, is a principal procedure for the assessment of integrated vulnerability. Finally, a variation of TSTC for both the SMRS and road networks will be calculated by implementing switches in transport mode resulting from partially unavailable SMRS.

7.1 Scenarios for a Disrupted SMRS

The O/D matrix is basically composed of a starting point at which travelling begins and an ending point at which travelling finishes. The O/D matrix is also classified by transport mode: car, scheduled bus, another bus, taxi, truck, the SMRS (including transfers between SMRS and bus). This work assumes 1,237 traffic zones and that all zones can be both origins and destinations. Consequently, each transport mode is structured as a format of 1,237 rows and 1,237 columns with traffic volumes by origin and destination. In other words, a change of available transport modes must cause different cell values in the O/D matrix.

When there is a disruptive event on the SMRS, parts of it cannot be used and travellers are required to choose alternative transport modes instead. Modal shift may happen within a specific area, depending on the scope of the disruption to the SMRS. A traveller who normally takes the SMRS may continue their original trip by driving their own car when they cannot use the SMRS because of the partial disruption. Other travellers can still use the SMRS because the disruptive event does not impact their normal trip route. Therefore, a description of the exact disruptive event is necessary in order to limit the analysis and revise the O/D matrix appropriately.

An updated O/D matrix can be produced by the assumed scenario. For example, if there is a disruptive event on the 1st Incheon axis of the SMRS, all trips originating in Incheon/Bucheon/Gimpo or whose destinations are Incheon/Bucheon/Gimpo, are modified from the normal traffic volume on the SMRS by the alternative mode ratios. Therefore, details of the disrupted SMRS need to be defined to understand the outcomes of before/after disruption.

Table 7-1. Scenario of Disruptions on SMRS

Transport Axis	Disrupted Section	No. of Stations	Duration	SMRS
1st Incheon	Incheon ~Onsu	17	1day (05:00~04:59 on next day)	SMRS Line 1
2nd Suwon	Oido ~Sadang	24	1day (05:00~04:59 on next day)	SMRS Line 4
3rd Seongnam	Suwon ~Suseo	25	1day (05:00~04:59 on next day)	Boondang Line
4th Namyangju	Yongmun ~Mangwoo	17	1day (05:00~04:59 on next day)	Gyeongui-Joongang Line
5th Uijeongbu	Soyosan ~Dobongsan	14	1day (05:00~04:59 on next day)	SMRS Line 1
6th Goyang	Daehwa ~Gupabal	12	1day (05:00~04:59 on next day)	SMRS Line 3

Table 7-1 gives the scenario of disruptions on the SMRS for each transport axis. These scenarios were conceived by considering the real disruptive events that were listed in Table 3-12. Basically, the disrupted sections of the SMRS were chosen as the start station of each transport axis to the boundary between Seoul its satellite cities. It is at the boundary of Seoul and its neighbouring cities that operation companies generally change. Furthermore, where a disruption is at a specific station, several stations in a section are halted for repair work. The scenario of disruptions on the SMRS was selected after considering the real data on disruptions, the operational characteristics, and the goal of this research to identify vulnerability of transport networks along the six transport axes.

If there is a different line of the SMRS close to the original line, that line may be a suitable alternative for travellers. Otherwise, they would move toward road networks to continue their trips using different transport modes: bus, car, taxi, and so on. Eventually, substitution for a specific line of the SMRS depends on the circumstances of the entire transport network and personal socio-economic situation.

1st Incheon axis consists of SMRS Line 1, Seoul Metro Line 7, Incheon Metro Line 1, Incheon Airport Railway, and Suin Line. SMRS Line 1 starts at Incheon Seaport and reaches to the CBD of Seoul Metropolitan City, connecting Incheon Metropolitan City, Bucheon City, and Seoul Metropolitan City. SMRS Line 1 is one of the oldest and the most congested in the SMRS, being operated with normal trains and express trains. Normal trains stop at every station, but express trains stop only at major transfer stations. Seoul Metro Line 7 begins at the centre of 1st Incheon transport axis and passes the southern part of Seoul Metropolitan City. Incheon Metro Line 1 improves relatively weak railway networks in the east-west direction by connecting Songdo International District and Gyeyang Station. Incheon

Airport Railway starts from Incheon International Airport and is connected to Seoul Station, via Gimpo International Airport, passing the northern part of 1st Incheon axis area.

Among diverse lines, SMRS Line 1 was constructed first and is a core line to access Seoul through the 1st Incheon transport axis. Incheon Station is the first station of SMRS Line 1 in the Incheon region, while Onsu Station is a transfer station between SMRS Line 1 and Seoul Metro Line 7. In addition, Onsu station is located on the boundary of Seoul on the Incheon side. Therefore, the first disruption scenario assumed that the section of SMRS Line 1 from Incheon Station to Onsu Station was out of service for one day.

Figure 7-1. Disruption Scenario of 1st Incheon Axis

Source: Seoul Metropolitan Rapid Transit Corp. http://www.smrt.co.kr/ (adapted, 2016)

2nd Suwon axis consists of SMRS Line 1, SMRS Line 4, Boondang Line, Shin Boondang Line, and Suin Line. SMRS Line 4 is the most important railway network from the perspective of availability in this axis. It passes through most cities in the Suwon axis and is a major line for commuting from west-southern part of the SCA to Seoul. Oido Station is a starting station and Sadang Station is a transfer station between SMRS Line 4 and Seoul Metro Line 2. In addition, Sadang station is located on the boundary of Seoul from the direction of Suwon axis. Therefore, the second disruption scenario assumed that the section of SMRS Line 4 from Oido Station to Sadang Station was out of service for one day.

SMRS Line 1 in the 2nd Suwon axis has the function of connecting the southern part of South Korea to Seoul Metropolitan City, which means it is less useful in transporting travellers intra-regionally. Boondang Line starts at Suwon Station and terminates at the eastern part of Seoul Metropolitan City, via Seongnam City. In other words, Boondang Line principally connects the southern part of the SCA in the east-west direction. Big cities in the southern part of the SCA are Ansan City, Suwon City, and Seongnam City. Suin Line has a similar function by connecting Incheon Metropolitan City and Ansan City. People can transfer to SMRS Line 4 at Oido station and continue their travels to Suwon City. Sin Boondang Line also links Suwon City, Seongnam City, and Seoul Metropolitan City, a very similar function to the Boondang Line but at a different geographic location.

Figure 7-2. Disruption Scenario of 2nd Suwon Axis

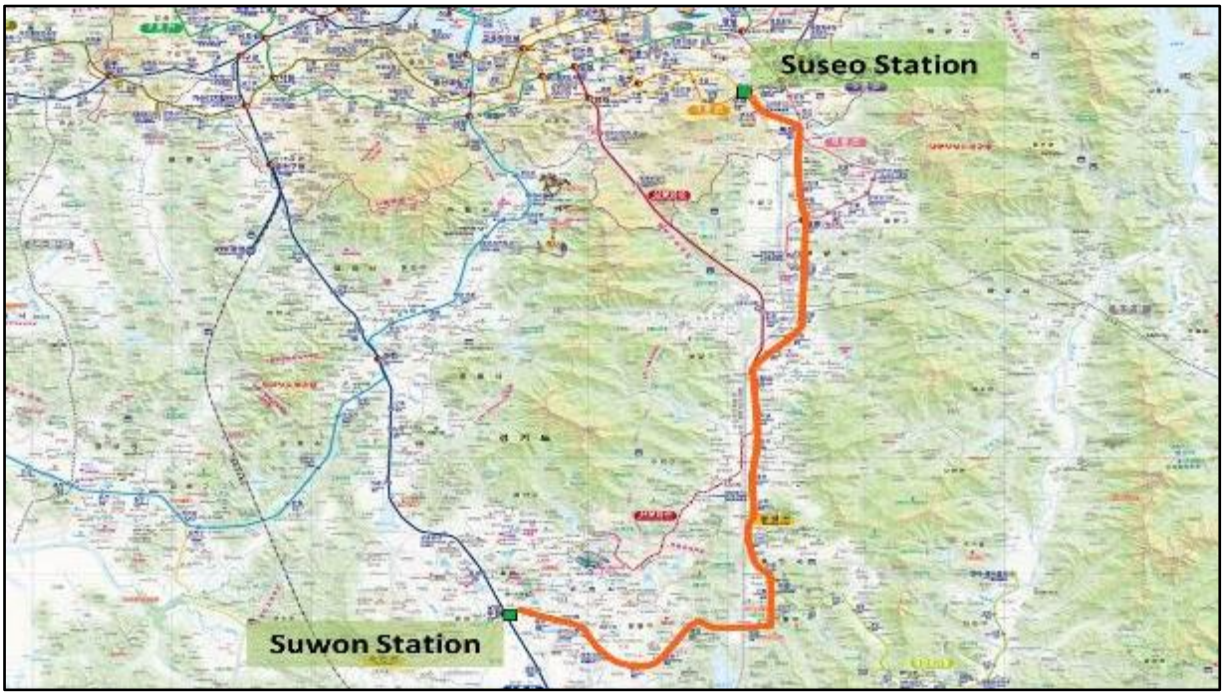
Source: Seoul Metropolitan Rapid Transit Corp. http://www.smrt.co.kr/ (adapted, 2016)

3rd Seongnam axis consists of Boondang Line, Shin Boondang Line, Yongin Light Railway, and Seoul Metro Line 8. Those lines mainly link Seongnam and Yongin toward Seoul but there is no direct SMRS line in Gwangju. Travellers from Gwangju have to use other access transport modes to take the SMRS.

Boondang Line is the major subway network within this axis, connecting Suwon, Yongin, Seongnam, and the eastern part of Seoul Metropolitan City in the north-south direction. Shin Boondang Line is a supplementary subway for linking Suwon, Seongnam, and the central part of Seoul Metropolitan City. Shin Boondang Line also functions to decrease the burden of Gyeongbu Expressway, the most congested expressway in Korea. Shin Boondang Line is famous for its unmanned operation and is privately financed. Yongin Light Railway connects Yongin City to the SMRS and is privately financed. Seoul Metro Line 8 has seven stations in this axis to link the eastern part of Seoul Metropolitan City and Seongnam City.

Suseo Station is a transfer station between Boondang Line and SMRS Line 3. Therefore, the third disruption scenario assumed that the section of the Boondang Line from Suwon Station to Suseo Station was out of service for one day.

Figure 7-3. Disruption Scenario of 3rd Seongnam Axis



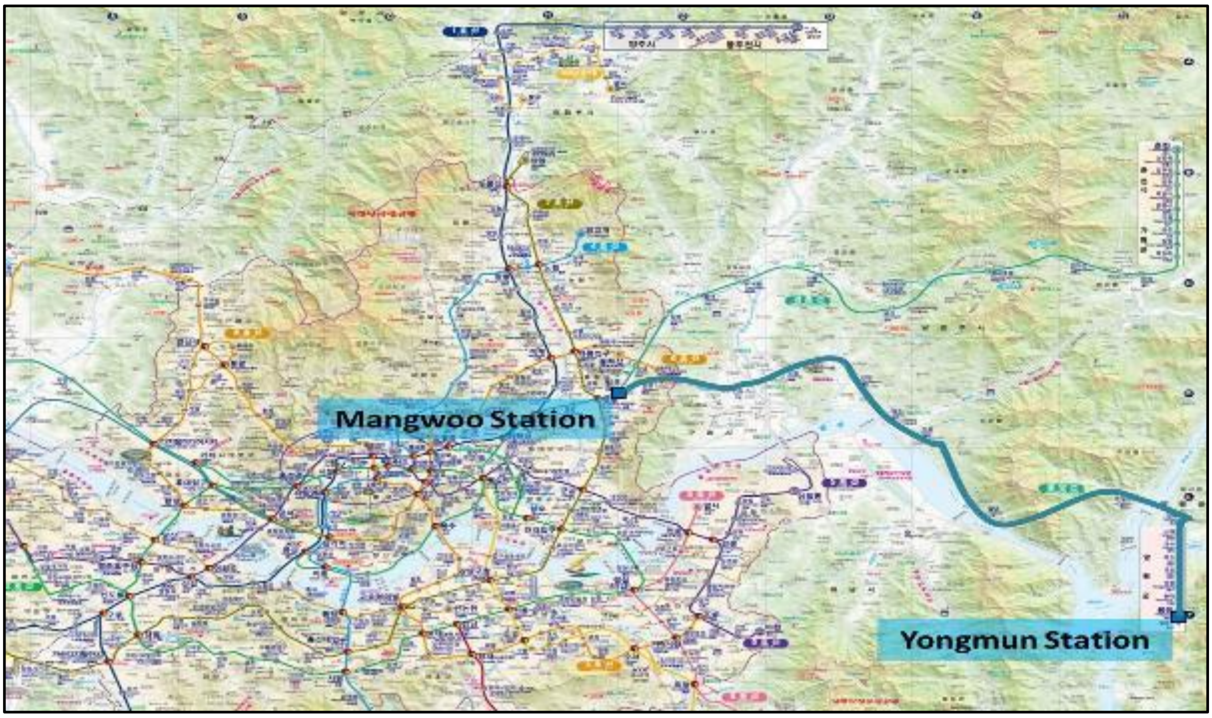
Source: Seoul Metropolitan Rapid Transit Corp. http://www.smrt.co.kr/ (adapted, 2016)

4th Namyangju axis consists of Gyeongui-Joongang Line, Gyeongchun Line, and Seoul Metro Line 5. Gyeongui-Joongang Line passes Yangpyeong County, Namyangju City, and Guri City, connecting to Seoul Metropolitan City. Gyeongchun Line starts from Gangwon Province and connects Namyangju City, and Guri City, to Seoul Metropolitan City. Both Gyeongui-Joongang Line and Geyongchun Line were general railways but they have been transformed to electric railways recently. Joongang Line and Geyongchun Line have a similar function within this axis although their locations are different.

Since all stations of Seoul Metro Line 5 are located in Seoul, commuters should use other accessing modes to get to the line. For instance, travellers from Hanam City usually access Seoul Metro Line 5 after using bus-rapid transits between Hanam City and Seoul Metropolitan City.

Mangwoo Station is a transfer station between Gyeongui-Joongang Line and Chyeongchun Line. Even though there are three different SMRS lines in this transport axis, it is difficult for the three lines to be alternatives when there is a disruptive event because connecting transport infrastructures are poorly developed. Therefore, the fourth disruption scenario assumed that the section of the Gyeongui-Joongang Line from Yongmun Station to Mangwoo Station was out of service for one day.

Figure 7-4. Disruption Scenario of 4th Namyangju Axis



Source: Seoul Metropolitan Rapid Transit Corp. http://www.smrt.co.kr/ (adapted, 2016)

5th Uijeongbu axis consists of SMRS Line 1, Uijeongbu Light Rail, SMRS Line 4, and Seoul Metro Line 7, having a distinguished function within this axis. Uijeongbu axis is located in a north-south direction from Seoul Metropolitan City to Dongducheon City because the cities in the Uijeongbu axis are surrounded by high mountains. SMRS Line 4 and Seoul Metro Line 7 have the last station at the boundary of Seoul Metropolitan City and Gyeonggi Province.

Uijeongbu Light Rail was constructed to satisfy transport demands within Uijeongbu City in an east-western direction. All stations of Uijeongbu Light Rail are located in Uijeonbu City.

SMRS Line 1 is the only railway network that connects Dongducheon City, Yangju City, Uijeongbu City, and Seoul Metropolitan City. In other words, SMRS Line 1 is the major transport network of the 5th Uijeongbu axis. SMRS Line 1 and Seoul Metro Line 7 are almost parallel in the 5th axis area. SMRS

Line 4 intersects SMRS Line 1 and Seoul Metro Line 7 in an east-west direction and travellers can transfer in order to access the CBD of Seoul Metropolitan City.

Dobongsan Station is a transfer station between SMRS Line 1 and Seoul Metro Line 7, located at the entrance of Seoul from the northern SCA. Therefore, the fifth disruption scenario assumed that the section of the SMRS Line 1 from Soyosan Station to Dobongsan Station was out of service for one day.

Figure 7-5. Disruption Scenario of 5th Uijeongbu Axis

Source: Seoul Metropolitan Rapid Transit Corp. http://www.smrt.co.kr/ (adapted, 2016)

Lastly, 6th Goyang axis' consists of SMRS Line 3 and Gyeongui-Joongang Line. Before December 2014, there was only SMRS Line 3 serving the Goyang axis area. SMRS Line 3 comprises two lines: Seoul Metro Line 3, and Ilsan Line. Seoul Metro Line 3 is operated by the Seoul Metro Corporation from Jichuk Station to Ogeum Station, and is 38.2 km long. Ilsan Line is operated by KORAIL, and is 19.2 km from Daehwa Station to Jichuk Station. SMRS Line 3 is the major infrastructure that connects Goyang City to Seoul Metropolitan City.

Gyeongui-Joongang Line was opened in December 2014 with 53 stations along 124.5 km, becoming second[13] longest line in the SMRS. This line connects Paju City, Goyang City, Seoul Metropolitan City, Guri City, Namyangju City, and Yangpyeong County in the east-west direction. However, within the 6th

[13] SMRS Line 1 is the longest at 200.6 km with 98 stations. It goes from Seoul in all directions except eastbound. This line covers Choongnam Province, Gyeonggi Province, Incheon Metropolitan City and Seoul Capital City.

transport axis, fewer travellers use Gyeongui-Joongang Line than SMRS Line 3 because of the low population density nearby.

Therefore, the sixth disruption scenario assumed that the section of the SMRS Line 3 from Daehwa Station to Gupabal Station was out of service for one day.

Figure 7-6. Disruption Scenario of 6th Goyang Axis

Source: Seoul Metropolitan Rapid Transit Corp. http://www.smrt.co.kr/ (adapted, 2016)

7.2 Integrated Vulnerability of the Major Transport Axes

The integrated vulnerability of transport networks means the summation of disruptions' impact in terms of TSTC on both SMRS and its related road networks. Mode transfer from the unavailable SMRS to road networks is regarded as a major factor that increases TSTC. When there is a disruption to a section of the SMRS, travellers have to change their initial transport mode, the SMRS, to alternative transport modes that may be based on road networks. In other words, regular users of the SMRS may drive cars or take the bus when a disruptive event happens on their main travelling line.

Mode transfer from the SMRS to road networks can cause increased travel time costs as well as operating costs for car travellers, road traffic accident costs, environmental impact costs, and parking costs. These impacts formulate the equation of TSTC, as described in Equation 5-1. For the calculation of each part of TSTC, it is necessary to assume values for some parameters: value of travel time, average passenger number in vehicles, operating cost function, unit road traffic accident occurrence rate and unit traffic accident cost rate, and environmental impact cost function.

Value of travel time is based on the assumption that different transport mode users have different willingness to pay for saving travel time. Even though every traveller in the same transport modes may have different value of travel time, most transport analyses have applied the same value of travel time within the same transport modes, for pragmatic reasons. Generally, the value of travel time of car users is higher than that of the SMRS (KDI, 2015). It is also important to take into account the average number of passengers in vehicles when passengers of the SMRS are transformed into other transport modes of road networks. Values are different according to kinds of vehicle. Although there are several methods to estimate VTT (Wardman, 1998; Abrantes and Wardman, 2011), all the public infrastructure projects in Korea follow the guideline for a preliminary feasibility study from the Korea Development Institute. KDI has performed all the preliminary feasibility studies for publicly-financed infrastructure projects having total project costs of more than 50 billion KRW.

Table 5-1illustrates the VTT that has been applied to all publicly-financed projects. All the values of current standard were calculated from the VTT in 2013 using consumer price index (CPI) of 2014 and 2015. The average value of travel time (AVTT) for cars/taxis, buses and trucks in 2015 are 15,255 KRW/vehicle-hr, 90,736 KRW/vehicle-hr and 16,704 KRW/vehicle-hr respectively. Travellers on SMRS have an AVTT of 6,039 KRW/vehicle-hr.

Table 5-1. Value of Travel Time in Korea

Classification	Base Year	Unit	Cars/Taxis	Buses	Truck	SMRS (perperson)

			B	NB	D	B	NB	B	B	NB
Passenger	2013	Person/vehicle	0.22	1.02	1.00	0.23	13.26	1.00	0.05	0.95
Value of Travel Time	2013	KRW/man-hour	22,775	9,748	17,260	22,775	5,011	16,374	22,775	5,033
		KRW/vehicle-hr	5,011	9,943	17,260	5,238	66,446	16,374	1,139	4,781
Average Value of Travel Time	2013	KRW/vehicle-hr	14,954		88,944			16,374	5,920	
	2014	KRW/vehicle-hr	15,148		90,100			16,587	5,997	
	2015	KRW/vehicle-hr	15,255		90,736			16,704	6,039	

The operating cost function for road networks and the environmental impact cost function for road networks have similar forms. Both functions vary with vehicle speed, having a polynomial function relationship with speed. Coefficients of these functions are defined for each road transport mode. However, TSTC for road traffic accidents are determined by unit traffic accident occurrence rate and unit traffic accident cost rate, according to traffic accident types and road types (MOLIT, 2013).

Table 7-2 is a summary of the integrated vulnerability of transport networks in the SCA. In the normal situation, TSTC were to 353.29 billion KRW daily. In other words, all travellers in the SCA spent an equivalent of 353.29 billion KRW on travel per day. A disruptive event on the 1st Incheon axis increased the TSTC to 366.61 billion KRW, a 3.8% increase, the largest change in the six transport axes. However, a disruptive event on the 5th Uijeongbu axis increased the TSTC to 358.40 billion KRW, a 1.4% increase, the smallest of the six transport axes. Moreover, since these results are incurred due to disruptions on each transport axis during one day, it is difficult to find a pattern of the Downs-Thomson paradox, which means that the average travel time using cars roughly equals the average travel time by using public transport (Mogridge *et al.*, 1987).

Table 7-2. Total Social Travel Costs incurred by Disruption, by Transport Axis

(unit : 1 billion KRW/day)

Cost Classification		Total Social Travel Cost (TSTC)						
		Normal Situation	Disruptions in Incheon Axis (1st)	Disruptions in Suwon Axis (2nd)	Disruptions in Seongnam Axis (3rd)	Disruptions in Namyangju Axis (4th)	Disruptions in Uijeongbu Axis (5th)	Disruptions in Goyang Axis (6th)
Road	Travel Time	144.80	154.03	153.18	150.24	148.91	148.56	149.49
	Operation	109.63	114.15	113.62	111.93	111.17	110.92	111.46
	Traffic Accident	11.17	11.55	11.50	11.31	11.25	11.23	11.27
	Environment	45.21	46.65	46.51	45.99	45.75	45.69	45.86
	Parking	1.36	1.42	1.39	1.38	1.37	1.37	1.38
	Subtotal of Road Traffic	312.17	327.80	326.20	320.85	318.45	317.76	319.46
SMRS	Non-Vehicle Travel Time	16.42	15.02	15.32	15.61	16.14	16.15	16.05
	In Vehicle Travel Time	9.50	8.59	8.71	8.83	9.29	9.30	8.96
	Operation	15.21	15.20	15.18	15.19	15.18	15.19	15.20
	Subtotal of SMRS	41.12	38.81	39.21	39.63	40.61	40.64	40.21
TSTC	Total Amount	353.29	366.61	365.41	360.48	359.06	358.40	359.67
	Gross Increase	-	13.32	12.12	7.19	5.77	5.11	6.38
	Increase Rate		3.8%	3.4%	2.0%	1.6%	1.4%	1.8%
	Rank by G.I.	-	1	2	3	5	6	4
	Increase per Person (KRW)	-	3,259.07	2,623.95	3,224.70	5,411.27	5,753.85	4,538.90
	Rank by I.p.P	-	4	6	5	2	1	3
Population			4,086,928	4,618,200	2,230,362	1,065,892	888,379	1,405,418

(1million GBP ≒ 1.4 billion KRW, 2015 Budget of South Korean Government : 378 trillion KRW)
*G.I: Gross Increase, I.p.P: Increase per Person

A detailed review of results by transport axis now follows, in order of rank from Table 7-2 (1, 2, 5, then 3, 4, and 6).

7.2.1 Integrated Vulnerability of the 1st Incheon Transport Axis

The 1st Incheon axis experienced the greatest increase of TSTC of the six transport axes. TSTC of the normal situation was equivalent to 353.29 billion KRW for the day. A disrupted 1st Incheon axis increased the TSTC to 366.61 billion KRW. It is important to examine the road networks and the SMRS facilities in this axis to understand the result, because the increase was produced in the road networks.

Figure 7-7. Major Road Networks of 1st Incheon Axis

Source: http://map.naver.com/

Interruption to the 1st Incheon axis means unavailability of 17 stations, from Incheon Station to Onsu Station of SMRS Line 1. Seoul Metro Line 7 and Incheon Airport Railway can be alternative railway networks within the SMRS. However, since about 70% of the SMRS travellers wanted to use road networks with cars, taxi or bus in a disruptive environment, road networks of 1st Incheon axis should be considered when integrated vulnerability is assessed. The 1st Incheon axis area is connected to Seoul by the following major roads: Olympic Highway, Incheon Airport Expressway (E130), Kyeongin Expressway (E120), 2nd Kyeongin Expressway (E110), 3rd Kyeongin Expressway (E330), 6th National Highway, 46th National Highway, and 48th National Highway. It is clear that Incheon axis is supported by relatively well-organised road networks.

Table 7-3 summarises the result of all link flows by transport mode in the 1st Incheon axis' disruption. Although bus with scheduled route experience no change of link flows, all other transport modes on the road networks increase by mode transfers from the disrupted SMRS. Note: our assumption is that no extra scheduled buses are provided and the increase in demand for buses is fully satisfied by providing chartered buses (Other Bus) and more crowded scheduled bus.

The total of vehicles on all links is 698,837,500 in a normal situation. This is changed to 725,224,488 in the 1st Incheon axis's disruption, an increase of 3.8%. Conversely, the total of passengers who use the SMRS decreases from 90,278,605 to 82,408,469, an 8.7% decrease.

Table 7-3. Link Flows by Mode in 1st Incheon Axis' Disruption

(unit : vehicles in road, passengers in SMRS)

Classification		Normal Situation			1st Incheon Axis' Disruption		
		Link_AB	Link_BA	Total	Link_AB	Link_BA	Total
Road	Car	291,744,079	209,885,039	501,629,118	302,786,190	217,254,218	520,040,408
	Bus with Regular Route	22,404,305	19,101,618	41,505,923	22,404,305	19,101,618	41,505,923
	Other Bus	2,419,555	1,089,308	3,508,863	3,127,541	1,514,431	4,641,972
	Taxi	28,741,089	23,237,459	51,978,548	32,780,193	26,060,611	58,840,804
	Truck	63,247,958	36,967,090	100,215,048	63,248,699	36,946,683	100,195,382
	Subtotal of Road Traffic	408,556,986	290,280,514	698,837,500	424,346,927	300,877,561	725,224,488
SMRS	Non-vehicle Travel	22,604,575	22,903,999	45,508,574	20,650,083	21,020,627	41,670,711
	In-vehicle Travel	-	-	44,770,031	-	-	40,737,758
	Subtotal of SMRS Traffic	-	-	90,278,605	-	-	82,408,469

For the car only, there is a 3.7% increase from 501,629,118 to 520,040,408 vehicles, and Other Bus experiences the highest increase at 32.3%, from 3,508,863 to 4,641,972 buses. Taxi passengers show 13.2% growth from 51,978,548 to 58,840,804. For the SMRS, non-vehicle travel drops 8.4% (from 45,508,574 to 41,670,711) and in-vehicle travel decreases 9.0% (from 44,770,031 to 40,737,758).

Table 7-4 shows that the TSTC of the 1st Incheon axis' transport networks experience an increase of 13.32 billion KRW, from 353.29 to 366.61 billion KRW/day, as a result of Scenario 1. The increase is a 3.8% rise, the highest of the six transport axes. This ranking drops to fourth place after the increases TSTC is divided by its population. In other words, the 1st Incheon transport axis is less vulnerable compared to other transport axes in the SCA. If the disruptive situation continues for one week, increased social travel cost would surge to 93.24 billion KRW.

There is a 5.0% increase, of 15.63 billion KRW/day, on road networks. Of the five factors, TSTC from travel time comprises 59.1% of the TSTC increase in road networks, followed by TSTC from operating cost factors, TSTC from environmental impact factor, and traffic accident factor. However, for the SRMS there is a 5.6 % decrease of TSTC, or 2.31 billion KRW/day. Travellers who board, leave, or transfer within the SMRS produce an 8.5% decrease of TSTC. Additionally, passengers on the SMRS decrease to 9.5% compared with the normal situation on the SMRS, but the operating costs of the SMRS only decrease by 0.1%.

Table 7-4. Total Social Travel Costs caused by 1st Incheon Axis' Disruption

(unit : billion KRW, %)

Classification		Total Social Travel Cost (TSTC)				
		Normal Situation	Disruptions in Incheon Axis (1st)	Increace of TSTC/day	Rate of Increase	Increace of TSTC/week
Road	Travel Time	144.80	154.03	9.23	6.4%	64.58
	Operation	109.63	114.15	4.52	4.1%	31.63
	Traffic Accident	11.17	11.55	0.38	3.4%	2.68
	Environment	45.21	46.65	1.44	3.2%	10.10
	Parking	1.36	1.42	0.06	4.4%	0.42
	Subtotal of Road Traffic	312.17	327.80	15.63	5.0%	109.41
SMRS	Non-Vehicle Travel Time	16.42	15.02	-1.40	-8.5%	-9.79
	In Vehicle Travel Time	9.50	8.59	-0.90	-9.5%	-6.30
	Operation	15.21	15.20	-0.01	-0.1%	-0.08
	Subtotal of SMRS	41.12	38.81	-2.31	-5.6%	-16.17
Total Social Travel Cost (TSTC)		353.29	366.61	13.32	3.8%	93.24

(1million GBP ≒ 1.4 billion KRW, 2015 Budget of South Korea Government : 378 trillion KRW)

In order to verify the reliability of trip assignment in both the normal situation and Scenario 1, it is useful to check the travel time of a specific origin/destination pair. A trip from Incheon station to Seoul Metropolitan City Hall Station is an appropriate example for checking travel time costs. The distance between them is about 40 km. Table 7-5 shows the travel times identified by TransCAD.

According to the Table 7-5, the travel time for an car traveller was 51.61 minutes and the travel time for a SMRS traveller was 62.52 minutes in the normal situation. These travel time could be converted to the TSTC from travel time costs as much as 10,582 KRW and 6,293 KRW respectively (See Although there are several methods to estimate VTT (Wardman, 1998; Abrantes and Wardman, 2011), all the public infrastructure projects in Korea follow the guideline for a preliminary feasibility study from the Korea Development Institute. KDI has performed all the preliminary feasibility studies for publicly-financed infrastructure projects having total project costs of more than 50 billion KRW.

Table 5-1illustrates the VTT that has been applied to all publicly-financed projects. All the values of current standard were calculated from the VTT in 2013 using consumer price index (CPI) of 2014 and 2015. The average value of travel time (AVTT) for cars/taxis, buses and trucks in 2015 are 15,255

KRW/vehicle-hr, 90,736 KRW/vehicle-hr and 16,704 KRW/vehicle-hr respectively. Travellers on SMRS have an AVTT of 6,039 KRW/vehicle-hr.

Table 5-1. Value of Travel Time in Korea

Classification	Base Year	Unit	Cars/Taxis		Buses			Truck	SMRS (perperson)	
			B	NB	D	B	NB	B	B	NB
Passenger	2013	Person/vehicle	0.22	1.02	1.00	0.23	13.26	1.00	0.05	0.95
Value of Travel Time	2013	KRW/man-hour	22,775	9,748	17,260	22,775	5,011	16,374	22,775	5,033
		KRW/vehicle-hr	5,011	9,943	17,260	5,238	66,446	16,374	1,139	4,781
Average Value of Travel Time	2013	KRW/vehicle-hr	14,954		88,944			16,374	5,920	
	2014	KRW/vehicle-hr	15,148		90,100			16,587	5,997	
	2015	KRW/vehicle-hr	15,255		90,736			16,704	6,039	

for converting travel time to TSTC). When the section from Incheon station to Onsu station was malfunctioned, the travel time for the car traveller and the SMRS traveller increased as much as 58.07 minutes and 72.03 minutes respectively. If these increased travel time were computed into TSTC from travel time costs, they were 11,907 KRW and 10,827 KRW respectively.

The traveller who wanted to use the available section of the SMRS had to use road networks from Incheon station to Onsu station and experienced more increase of travel time, compared to the car traveller from Incheon station to Seoul Metropolitan City Hall station. In other words, there was not much difference of TSTC between travelling by car and using the SMRS in the case of disruptive events on the SMRS. This could be the basis for an information provision system, particularly if based on time segments rather than the all day average.

Table 7-5. Example of Travel Time Costs in Normal Situation and Disrupted 1st Incheon Axis

Normal Situation	Origin	Destination	Distance (km)	Travel Time (min.)	TSTC from Travel Time (KRW/traveller)	Monetary Costs (KRW/traveller)
Car	Incheon Station	Seoul Metropolitan City Hall Station	41.25	51.61	10,582	Toll: 900 Fuel: 5,405
SMRS	Incheon Station	Seoul Metropolitan City Hall Station	40.08	Initial wait time: 3.19 In-vehicle time: 59.33 Sum: 62.52	6,293	Fare: 1,850
Disrupted Situation in 1st Incheon Axis	Origin	Destination	Distance (km)	Travel Time (min.)	TSTC from Travel Time (KRW/traveller)	Monetary Costs (KRW/traveller)
Car	Incheon Station	Seoul Metropolitan City Hall Station	41.25	58.07	11,907	Toll: 900 Fuel: 6,082
Car	Incheon Station	Onsu Station	29.21	34.26	7,025	Toll: 900 Fuel: 3,588
SMRS	Onsu Station	Seoul Metropolitan City Hall Station	18.72	Transfer time: 10.83 Initial wait time: 3.19 In-vehicle time: 23.75 Sum: 37.77	3,802	Fare: 1,450

Figure 7-8 to Figure 7-12 were captured from the TransCAD analysis that provided the source of values in Table 7-5.

Figure 7-8. Travel Time for a Car from Incheon Station to Seoul Metropolitan City Hall Station, Normally

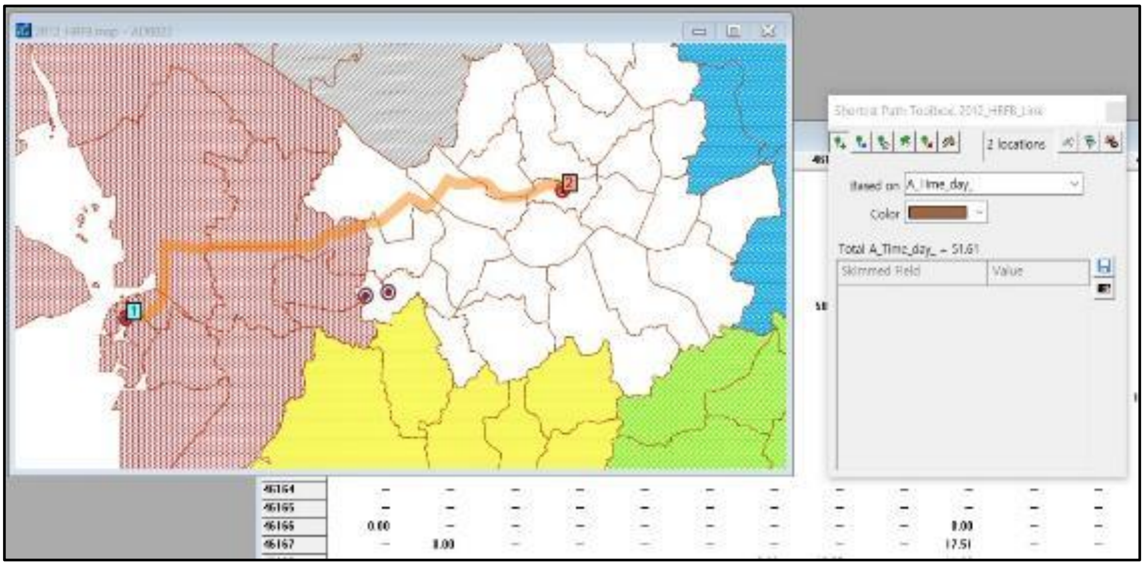


Figure 7-9. Travel Time for the SMRS from Incheon Station to Seoul Metropolitan City Hall Station, Normally

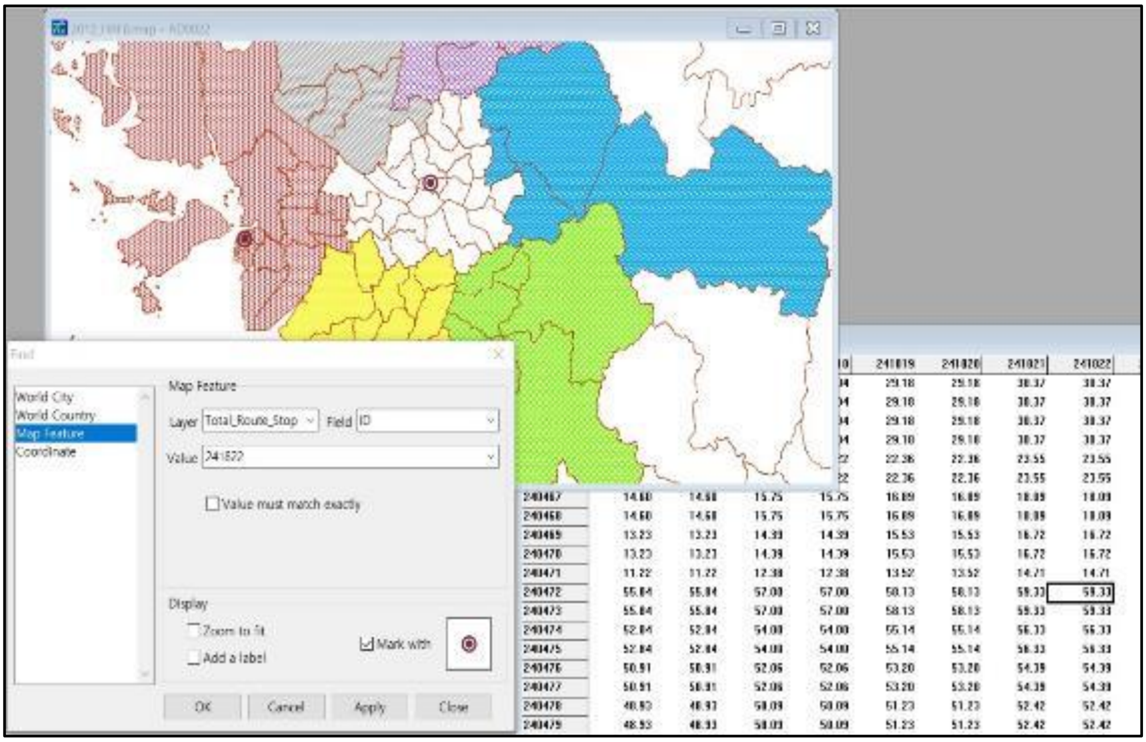


Figure 7-10. Travel Time for a Car from Incheon Station to Seoul Metropolitan City Hall Station, during a Disruption on 1st Incheon Axis

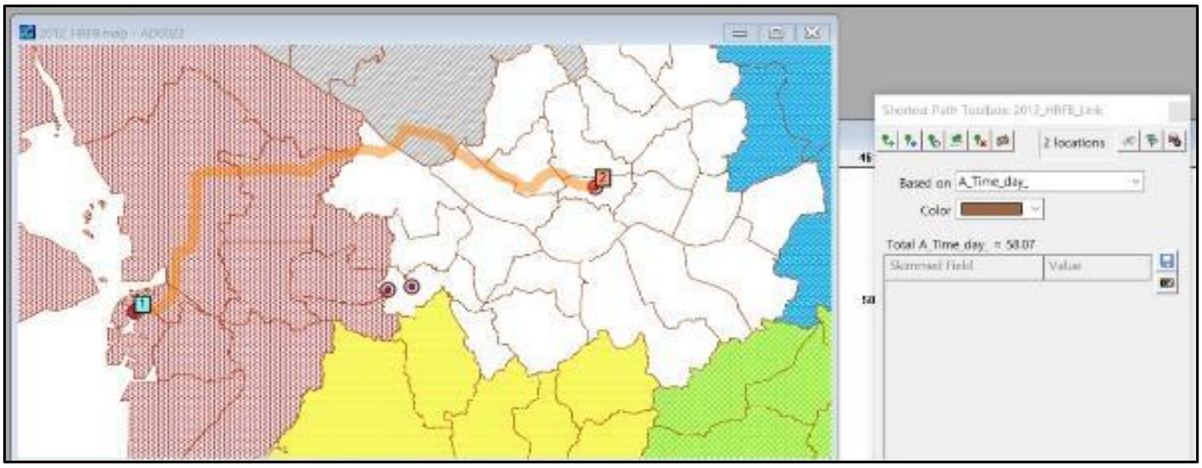


Figure 7-11. Travel Time for a Car from Incheon Station to Onsu Station during a Disruption on 1st Incheon Axis

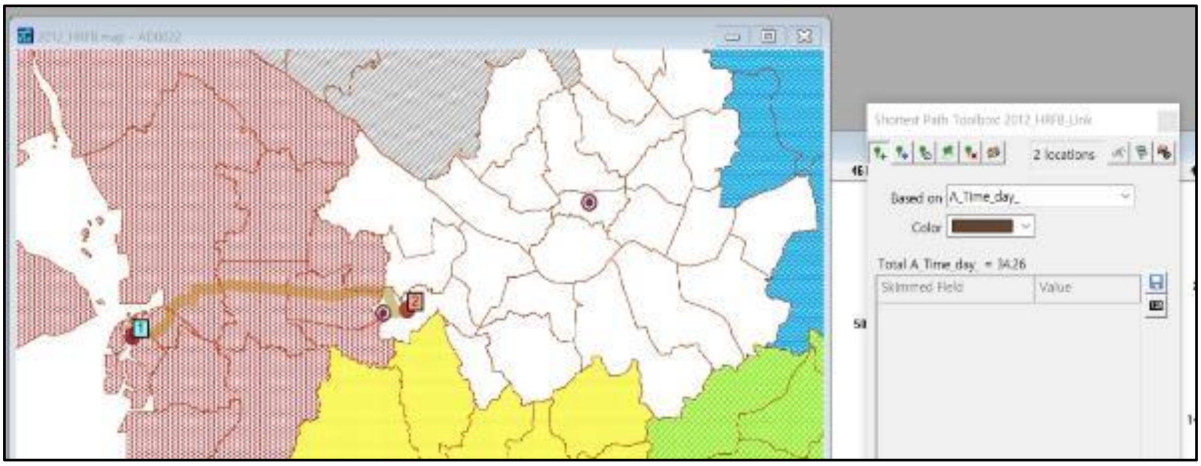
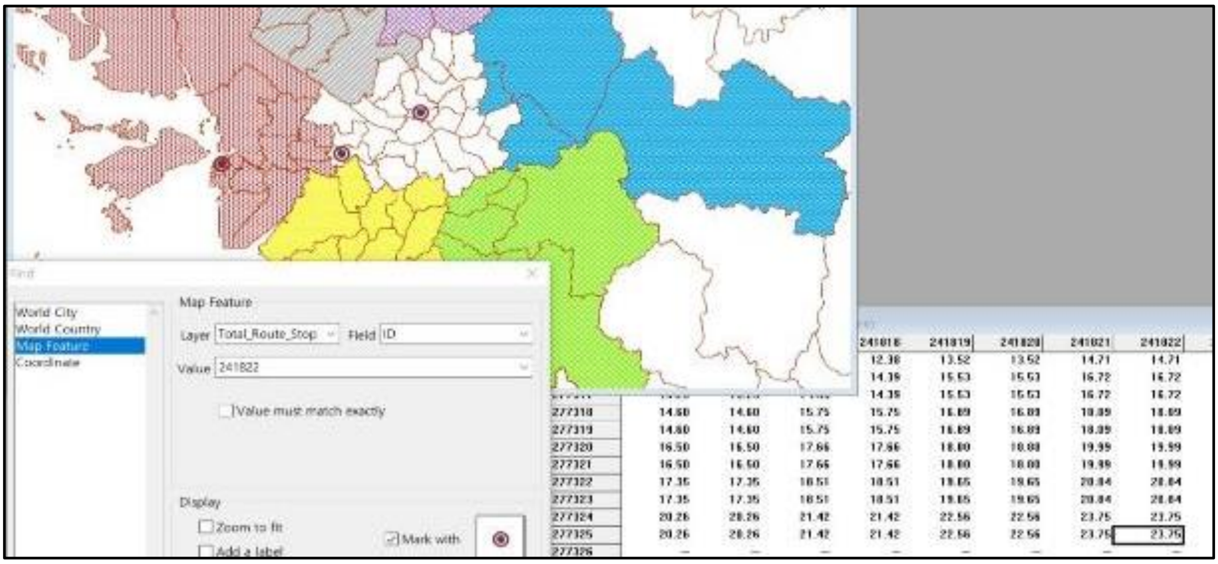


Figure 7-12. Travel Time for the SMRS from Onsu Station to Seoul Metropolitan City Hall Station during a Disruption on 1st Incheon Axis



7.2.2 Integrated Vulnerability of the 2nd Suwon Transport Axis

2nd Suwon axis recorded the second highest increase of TSTC. However, after being divided by its population, the 2nd Suwon axis showed the least rise of TSTC per capita. In other words, the effect of population changes the priority for infrastructure investment in achieving a more resilient transport network.

Scenario 2 addresses a disruption on the 2nd Suwon axis. This assumes that 24 stations, from Oido Station to Sadang Station of SMRS Line 4, are not available for one day. The 2nd Suwon axis has the largest population of the six transport axes and the most cities are located along this axis. It is supported by these well-connected road networks: Gyeongbu Expressway (E1), Seohaean Expressway (E15), Pyeongtaek-Siheung Expressway (E153), Pyeongtaek-Gwangmyeong Expressway (E17), Yongin-Seoul Expressway (E171), 1st National Highway, 39th National Highway, 42nd National Highway, 47th National Highway, Seobuganseon Highway, and Gwacheon-Bongdam Highway. For railway networks, this axis is supported by SMRS Line 1, SMRS Line 4, KTX Gyeongbu Line, and Suin Line. Although SMRS Line 4 connects major cities of the 2nd Suwon transport axis from west to east, other railway lines mainly pass through north-south.

Figure 7-13. Major Road Networks of the 2nd Suwon Axis

Source: http://map.naver.com/

Table 7-6 summarises the result of all link flows by transport mode in the 2nd Suwon axis' disruption. All transport modes on the road networks, except with scheduled bus route, increase by mode transfer from the disrupted SMRS. Note: our assumption is that no extra scheduled buses are provided and the increase in demand for buses is fully satisfied by providing chartered buses (Other Bus) and more crowded scheduled bus.

The total vehicles on all links are 698,837,500 normally. This is changed to 723,237,119 in the 2nd Suwon axis's disruption, an increase of 3.5%. Conversely, the total of passengers who use the SMRS decreases from 90,278,605 to 83,778,790.

Other Bus increases by a massive 45.9%, from 3,508,863 to 5,120,400 vehicles when the section from Oido Station to Sadang Station is not available. Taxis also see a 14.8% rise, from 51,978,548 to 59,653,389 journeys. Cars show a much lower increase at about 3.0% from 501,629,118 to 516,923,280 vehicles. SMRS-related trips decrease by 6.5% and in-vehicle travel decreases by 7.9%, compared to the normal situation.

Table 7-6. Link Flows by Mode in 2nd Axis' Disruption

(unit : vehicles in road, passengers in SMRS)

Classification		Normal Situation			2nd Suwon Axis' Disruption		
		Link_AB	Link_BA	Total	Link_AB	Link_BA	Total
Road	Car	291,744,079	209,885,039	501,629,118	301,010,117	215,913,163	516,923,280
	Bus with Regular Route	22,404,305	19,101,618	41,505,923	22,404,305	19,101,618	41,505,923
	Other Bus	2,419,555	1,089,308	3,508,863	3,392,150	1,728,250	5,120,400
	Taxi	28,741,089	23,237,459	51,978,548	33,199,592	26,453,797	59,653,389
	Truck	63,247,958	36,967,090	100,215,048	63,128,326	36,905,801	100,034,127
	Subtotal of Road Traffic	408,556,986	290,280,514	698,837,500	423,134,490	300,102,629	723,237,119
SMRS	Non-vehicle Travel	22,604,575	22,903,999	45,508,574	21,092,665	21,462,656	42,555,321
	In-vehicle Travel	-	-	44,770,031	-	-	41,223,469
	Subtotal of SMRS Traffic	-	-	90,278,605	-	-	83,778,790

A disruption to the 2nd Suwon axis causes the second largest increase of TSTC to 12.12 billion KRW/day, or 3.4% increase, from 353.29 to 365.41 (Table 7-2). This value increases to 84.83 billion KRW if the disruption lasts a week. However, if the TSTC is divided by Suwon axis' population, it changes from second position to last position when TSTC is measured per capita.

Putting it another way, the 2nd Suwon axis is the most stable one from the perspective of average vulnerability. The whole road network experiences an increase of 14.03 billion KRW/day, or a 4.5% increase. However, the SMRS reveals a decrease of 4.6% or 1.91 billion KRW/day (see Table 7-7).

TSTC from travel time shows a 5.8% increase, from 144.80 to 153.18 billion KRW, comprising 59.7% of the increase of whole TSTC on road networks. TSTC from operating costs of road networks is second with 3.6% increase, at 3.99 billion KRW. TSTC from road traffic accident is the smallest of the four factors, increasing 3.0% from 11.17 to 11.50 billion KRW. TSTCs from the SMRS decrease in both non-vehicle travel time and in vehicle travel time as a result of fewer passengers on the SMRS, dropping 6.7% and 8.3% respectively.

Table 7-7. Total Social Travel Cost caused by 2nd Suwon Axis' Disruption

(unit : billion KRW, %)

Classification		Total Social Travel Cost (TSTC)				
		Normal Situation	Disruptions in Suwon Axis (2nd)	Increace of TSTC/day	Rate of Increase	Increace of TSTC/week
Road	Travel Time	144.80	153.18	8.37	5.8%	58.60
	Operation	109.63	113.62	3.99	3.6%	27.92
	Traffic Accident	11.17	11.50	0.33	3.0%	2.33
	Environment	45.21	46.51	1.30	2.9%	9.13
	Parking	1.36	1.39	0.03	2.2%	0.21
	Subtotal of Road Traffic	312.17	326.20	14.03	4.5%	98.19
SMRS	Non-Vehicle Travel Time	16.42	15.32	-1.10	-6.7%	-7.71
	In Vehicle Travel Time	9.50	8.71	-0.79	-8.3%	-5.51
	Operation	15.21	15.18	-0.02	-0.1%	-0.15
	Subtotal of SMRS	41.12	39.21	-1.91	-4.6%	-13.36
Total Social Travel Cost (TSTC)		353.29	365.41	12.12	3.4%	84.83

(1million GBP ≒ 1.4 billion KRW, 2015 Budget of South Korea Government : 378 trillion KRW)

2015 Budget of South Korea Government: 378 trillion KRW

7.2.3 Integrated Vulnerability of the 5th Uijeongbu Transport Axis

The 5th Uijeongbu axis recorded the smallest increase in total TSTC of the six transport axes, but after being divided by its population, this axis produced the highest increase of TSTC per capita, see Table 7-2. To put it another way, the smallest magnitude of total TSTC came from the smallest population in the area and therefore the 5th Uijeongbu axis should not be excluded from additional infrastructure investment plans from a standpoint of transport impartiality.

Scenario 5 assumes that 14 stations, from Soyosan Station to Dobongsan Station of SMRS Line 1, are unavailable for use. The road networks in this transport axis are restricted because it is surrounded by widely mountainous area, with Bukhan Mountain and Dobong Mountain on west side and Bulam Mountain and Surak Mountain on the east side of the axis. Therefore, major road networks and railway networks traverse the lower levels, in the middle of this mountainous region. Road networks are: Seoul Ring Expressway (E100), 3rd National Highway, 43rd National Highway, 47th National Highway, and Dongbuganseon Highway. Dongbuganseon Highway is the main road network to central Seoul.

Figure 7-14. Major Road Networks of 5th Uijeongbu Axis

Source: http://map.naver.com/

Table 7-8 summarises the result of all link flows by transport mode in the 5th Uijeongbu axis' disruption. It can be seen that the variations for each transport mode are similar to those of the 1st Incheon axis or the 2nd Suwon axis. There are some differences of scale. The total vehicles on all links is 701,938,448 in the disruptive situation, only a 0.4% increase on 698,837,500 normally. Furthermore, the passengers who use the SMRS decrease to 88,593,566 in the disruptive situation.

The Scenario 5 disruptive event on the SMRS Line 1 with 5th Uijeongbu transport axis causes 0.4% increase of car use from 501,629,118 to 503,657,221 vehicles. Even Other Bus increases just 6.9%, from

3,508,863 to 3,751,588 vehicles. These increasing rates are quite small when compared to the other five transport axes. This trend was similar to the decrease of passengers on the SMRS. Non-vehicle travel passengers decrease only 1.3%, from 45,508,574 to 44,912,186. In-vehicle travel passengers also drop 2.4%, from 44,770,031 to 43,681,380. It seems that 5th Uijeongbu transport axis shows a small increase of each transport mode on road networks, and relatively strong adherence to the available SMRS networks. It is probable that people prefer travelling by rail to road networks because severe congestion on the limited alternatives within the road networks, as a consequence of the mountainous environment.

Table 7-8. Link Flows by Mode in 5th Uijeongbu Axis' Disruption

(unit : vehicles in road, passengers in SMRS)

Classification		Normal Situation			5th Uijeongbu Axis' Disruption		
		Link_AB	Link_BA	Total	Link_AB	Link_BA	Total
Road	Car	291,744,079	209,885,039	501,629,118	292,864,931	210,792,290	503,657,221
	Bus with Regular Route	22,404,305	19,101,618	41,505,923	22,404,305	19,101,618	41,505,923
	Other Bus	2,419,555	1,089,308	3,508,863	2,564,087	1,187,501	3,751,588
	Taxi	28,741,089	23,237,459	51,978,548	29,230,240	23,594,048	52,824,288
	Truck	63,247,958	36,967,090	100,215,048	63,265,600	36,933,828	100,199,428
	Subtotal of Road Traffic	408,556,986	290,280,514	698,837,500	410,329,163	291,609,285	701,938,448
SMRS	Non-vehicle Travel	22,604,575	22,903,999	45,508,574	22,285,719	22,626,468	44,912,186
	In-vehicle Travel	-	-	44,770,031	-	-	43,681,380
	Subtotal of SMRS Traffic	-	-	90,278,605	-	-	88,593,566

Scenario 5 increases TSTC to 5.11 billion KRW/day, a 1.4% increase, from 353.29 to 358.40. This value was the lowest gross increase of TSTC among the six axes. However, after dividing by its population, the increase of TSTC per person is 5,753.85 KRW/man-day, which means it is the most vulnerable axis (see Table 7-2). The increase would become 35.78 billion KRW if the disruption continued for one week. All road traffic increases by 5.59 billion KRW/day, or 1.8% increase (see Table 7-9).

TSTC from travel time increases 2.6%, from 144.80 to 148.56 billion KRW. TSTC from road traffic accidents remained almost the same in spite of the disruption. Subtotal of road networks TSTC increases 1.8%, from 312.17 to 317.76 billion KRW. In addition, TSTC from the SMRS for non-vehicle travel time drops 1.6%, from 16.42 to 16.15 billion KRW and for in vehicle travel time drops 2.1%, from 9.50 to 9.30 billion KRW. These small changes show a similar trend to traffic flows seen Table 7-8. The parallel layout of SMRS Line 1 and Seoul Metro Line 7 could be one of the reasons for the small change.

Table 7-9. Total Social Travel Cost caused by 5th Uijeongbu Axis' Disruption

(unit : billion KRW, %)

Classification		Total Social Travel Cost (TSTC)				
		Normal Situation	Disruptions in Uijeongbu Axis (5th)	Increace of TSTC/day	Rate of Increase	Increace of TSTC/week
Road	Travel Time	144.80	148.56	3.76	2.6%	26.30
	Operation	109.63	110.92	1.28	1.2%	8.98
	Traffic Accident	11.17	11.23	0.06	0.5%	0.42
	Environment	45.21	45.69	0.48	1.1%	3.36
	Parking	1.36	1.37	0.01	0.7%	0.07
	Subtotal of Road Traffic	312.17	317.76	5.59	1.8%	39.13
SMRS	Non-Vehicle Travel Time	16.42	16.15	-0.27	-1.6%	-1.87
	In Vehicle Travel Time	9.50	9.30	-0.20	-2.1%	-1.38
	Operation	15.21	15.19	-0.02	-0.1%	-0.11
	Subtotal of SMRS	41.12	40.64	-0.48	-1.2%	-3.36
Total Social Travel Cost (TSTC)		353.29	358.40	5.11	1.4%	35.78

(1million GBP ≒ 1.4 billion KRW, 2015 Budget of South Korea Government : 378 trillion KRW)

7.2.4 How to Strengthen the Most Vulnerable Transport Axis

The 1st Incheon transport axis was identified as the most vulnerable one in the SCA from the perspective of the gross increase of the TSTC. However, taking into account the increase of the TSTC per capita, the 5th Uijeongbu axis was found to be the most susceptible to a disruptive event on the SMRS. Some ideas for these two axes are suggested in order to relieve the impact of the disrupted SMRS, from the standpoint of supply and demand.

The 1st Incheon axis is characterised by having the highest preference for car travel among the six transport axes, the lowest preference for bus as an alternative mode, and high intention to use other SMRS services. These features can be explained by high connectivity of the current road networks and the SMRS within the 1st Incheon transport axis.

- Central government can increase the metro bus service that connects the Incheon corridor with Seoul Metropolitan City directly, by limiting the number of bus stops.

- Local government can also intensify the intra-city bus service to interconnect major transport hubs within the Incheon corridor, so that travellers can make detours around a disrupted section of the SMRS.

- Exclusive bus lanes can be adopted within the Incheon corridor to induce travellers to transfer from car to bus. Currently, exclusive bus lanes have only been operated in the 2nd Suwon and 3rd Seongnam axes, but it has resulted in a high preference for bus as an alternative transport mode.

From the demand side, despite its well-developed infrastructure, the 1st Incheon axis experienced the highest increase in the TSTC because it has the largest travel demand to Seoul Metropolitan City. If workplaces were located closer to home, commuting travel demand would be reduced and the TSTC could decrease where there was an SMRS disruption. Basically, workplaces should be equally distributed around the SCA and houses have to be available at a reasonable price where there are many opportunities for jobs.

One of the more plausible approaches is a policy that allows/encourages working at home without any discrimination of wage or promotion. Working at home needs to be strongly promoted, both socially as well as legally. The survey revealed that fewer than 1% of respondents said that they could work at home. Korea’s well-developed ICT infrastructure is a model environment for working at home. Application of a policy of working at home is not limited to the Incheon corridor, as it can be applicable to the entire SCA or even nationwide.

Another approach from the demand side is encouraging cycling (biking) as a commuting transport mode. Riding a bike instead of driving a car is environmentally-friendly as well as economically beneficial. In order to boost the use of bike as a major travelling mode, some bike-friendly measures are needed: enough bike sheds with a security system for safe keeping, bike lanes for securing safety of riders, changing rooms and shower room at workplaces or public stations for comfort, and drivers’ consideration for bike riders.

Notable characteristics of alternative mode shares in 5th Uijeongbu transport axis are: the lowest choice of car of the six transport axes, the highest preference for the other SMRS service, and low proportion of bus use. These results are mainly attributed to poor road networks and few alternatives except using the other SMRS lines within Uijeongbu corridor. To improve the poor road networks in this axis, central government commissioned the Guri-Pocheon Expressway in June 2017, a public-private partnership. Because it is difficult to construct new railway networks in the mountainous territory and because of low traffic demand, one solution is to construct passing tracks at several places on the SMRS Line 1 and the Seoul Metro Line 7. This will mitigate the impact of disruptive events on the SMRS.

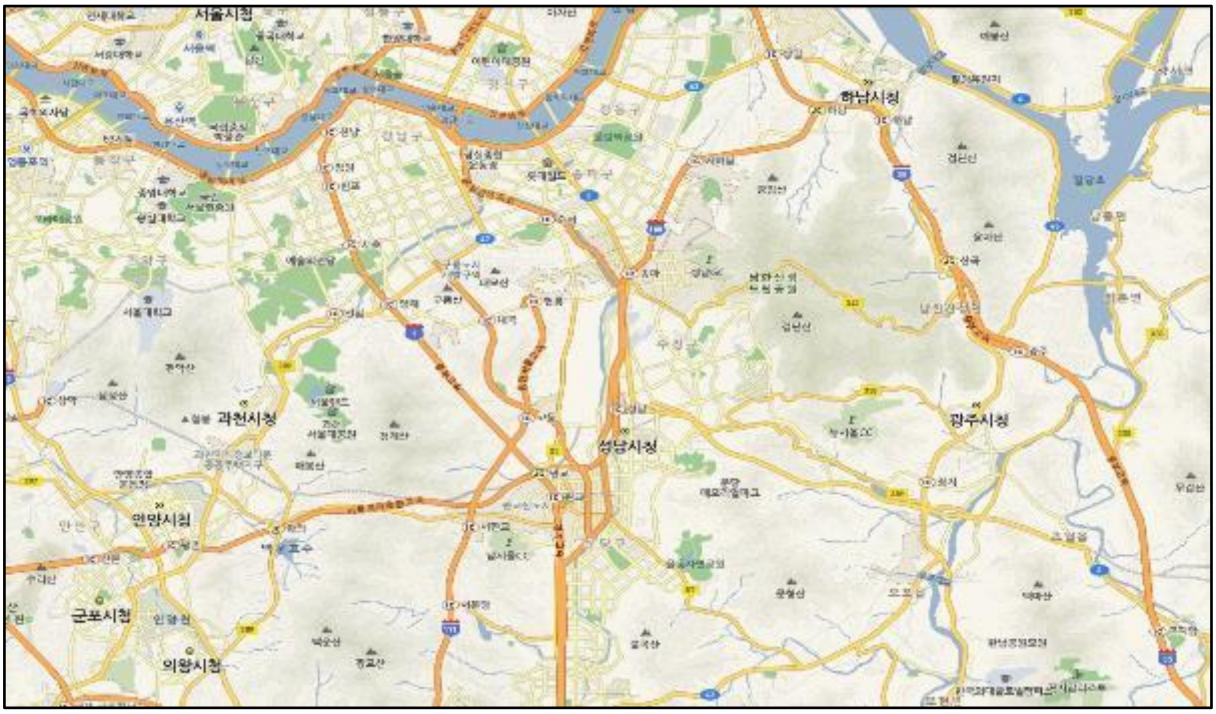
7.3 Integrated Vulnerability of the Remaining Transport Axes

7.3.1 Integrated Vulnerability of 3rd Seongnam Transport Axis

Scenario 3 is disruption of the 3rd Seongnam axis, when 25 stations are not available, from Suwon Station to Suseo Station of the Boondang Line. Despite mountains around this area, road networks in this axis are relatively well-developed when compared to 5th Uijeongbu axis. Road networks are: Gyeongbu Expressway (E1), Joongbu Expressway (E35), Yongin-Seoul Expressway (E171), Seoul Ring Expressway (E100), 3rd National Highway, 43rd National Highway, Dongbuganseon Highway, and Boondang-Naegok Highway.

For the railway networks, Shin Boondang Line has been operating since 2011, relieving the congestion of Boondang Line and Gyeongbu Expressway. Shin Boondang Line has long distances between statiosn compared to the Boondang Line, and is an automated operation without driver.

Figure 7-15. Major Road Networks of 3rd Seongnam Axis



Source: http://map.naver.com/

Table 7-10 summarises the result of all link flows by transport mode in the 3rd Seongnam axis' disruption. Trends for each transport mode are similar to the 1st Incheon axis or 2nd Suwon axis. However, there are some differences of scale. The total vehicles on all links is 710,154,113 during disruption, compared to

698,837,500 vehicles normally. All the passengers who use the SMRS decreases from 90,278,605 to 85,734,743 in the disruptive situation.

Other Bus showed the highest increase among road transport modes at 22.0%, from 3,508,863 to 4,279,530 vehicles. But the increase of Other Bus is smaller than that of 1st Incheon or 2nd Suwon axes. Car, taxi, and truck all show very little change in the disruptive event, at 1.6%, 5.2%, and –0.1% respectively.

For travellers on the SMRS, in-vehicle travel decreases 5.8%, from 44,770,031 to 42,185,476 passengers, while non-vehicle travel drops 4.3%, from 45,508,574 to 43,549,267 travellers.

Table 7-10. Link Flows by Mode in 3rd Seongnam Axis' Disruption

(unit : vehicles in road, passengers in SMRS)

Classification		Normal Situation			3rd Seongnam Axis' Disruption		
		Link_AB	Link_BA	Total	Link_AB	Link_BA	Total
Road	Car	291,744,079	209,885,039	501,629,118	296,548,959	213,031,709	509,580,668
	Bus with Regular Route	22,404,305	19,101,618	41,505,923	22,404,305	19,101,618	41,505,923
	Other Bus	2,419,555	1,089,308	3,508,863	2,904,849	1,374,681	4,279,530
	Taxi	28,741,089	23,237,459	51,978,548	30,406,160	24,258,417	54,664,577
	Truck	63,247,958	36,967,090	100,215,048	63,207,019	36,916,395	100,123,414
	Subtotal of Road Traffic	408,556,986	290,280,514	698,837,500	415,471,292	294,682,821	710,154,113
SMRS	Non-vehicle Travel	22,604,575	22,903,999	45,508,574	21,655,019	21,894,248	43,549,267
	In-vehicle Travel	-	-	44,770,031	-	-	42,185,476
	Subtotal of SMRS Traffic	-	-	90,278,605	-	-	85,734,743

Table 7-11 shows that disruption of 3rd Seongnam axis increases total TSTC to 7.19 billion KRW/day, a 2.0% increase, from 353.29 to 360.48 billion KRW/day. This changes to 50.34 billion KRW where the disruption extends to one week. This axis is the fifth lowest change of TSTC per capita, although the change in the gross TSTC is third. All road networks increases by 8.68 billion KRW/day, or 2.8%. However, SMRS decreases by 3.6% or 1.49 billion KRW/day.

TSTC from travel time in road networks increases 3.8%, from 144.80 to 150.24 billion KRW/day. The next value in order is the operating costs of road traffic, environmental impact costs, and road traffic accident costs in road networks. TSTC of non-vehicle travel time of the SMRS and TSTC of in vehicle travel time show similar changes to the flows seen in Table 7-10. TSTC from non-vehicle travel time drops 4.9%, from 16.42 to 15.61 billion KRW/day, while TSTC from in vehicle travel time decreases 7.0%, from 9.50 to 8.83 billion KRW/day.

Table 7-11. Total Social Travel Costs caused by 3rd Seongnam Axis' Disruption

(unit : billion KRW, %)

Classification		Total Social Travel Cost (TSTC)				
		Normal Situation	Disruptions in Seongnam Axis (3rd)	Increace of TSTC/day	Rate of Increase	Increace of TSTC/week
Road	Travel Time	144.80	150.24	5.43	3.8%	38.02
	Operation	109.63	111.93	2.30	2.1%	16.11
	Traffic Accident	11.17	11.31	0.14	1.2%	0.97
	Environment	45.21	45.99	0.79	1.7%	5.51
	Parking	1.36	1.38	0.02	1.5%	0.14
	Subtotal of Road Traffic	312.17	320.85	8.68	2.8%	60.75
SMRS	Non-Vehicle Travel Time	16.42	15.61	-0.80	-4.9%	-5.61
	In Vehicle Travel Time	9.50	8.83	-0.67	-7.0%	-4.66
	Operation	15.21	15.19	-0.02	-0.1%	-0.14
	Subtotal of SMRS	41.12	39.63	-1.49	-3.6%	-10.41
Total Social Travel Cost (TSTC)		353.29	360.48	7.19	2.0%	50.34

(1million GBP ≒ 1.4 billion KRW, 2015 Budget of South Korea Government : 378 trillion KRW)

2015 Budget of South Korea Government: 378 trillion KRW

7.3.2 Integrated Vulnerability of 4th Namyangju Transport Axis

While the 4th Namyangju axis was the second lowest measured by total TSTC, after being divided by its population, this axis showed the second biggest rise of TSTC per capita, after 5th Uijeongbu axis. Thus, a priority for infrastructure investment to make transport networks more resilient can differ a lot with or without consideration of the population of 4th Namyangju axis. Therefore, it would be helpful to know transport networks in this axis for a deeper understanding the result of TSTC analysis.

Scenario 4 is disruption of the 4th Namyangju axis when 17 stations are unavailable, from Yongmun Station to Mangwoo Station of the Gyeongui-Joongang Line. Another major railway network of this transport axis is Gyeongchun Line, which traverses the northern part of the axis. Since Gyeongui-

Joongang Line and Gyeongchun Line are far apart, they cannot compensate for each other. The road networks are: Joongbu Expressway (E35), Seoul-Chuncheon Expressway (E60), 6th National Highway, 43rd National Highway, 45th National Highway, 46th National Highway, Olympic Highway, Gankbyeonbukro Highway, Suseok-Hopyeong Highway, and Bookbu-Ganseon Highway.

Figure 7-16. Major Road Networks of 4th Namyangju Axis

Source: http://map.naver.com/

Table 7-12 summarises the result of all link flows by transport mode in the 4th Namyangju axis' disruption. Although the variation in link flows does not compare with other transport axes, the same trends were visible. The number of vehicles on all links increases by 0.7%, from 698,837,500 to 703,603504, during a disruption. On the other hand, passengers who use the SMRS decrease by 1.6%, from 90,278,605 to 88,871,078, during disruption.

Of the road transport modes, car showed the lowest increase at 0.5%, from 501,629,118 to 504,334,557 vehicles. The Other Bus is higher than other road transport modes, increasing 8.2%, from 3,508,863 to 3,794,977 vehicles. Taxi and truck showed small changes of 3.6% and –0.1% respectively. These trends are similar to the results for the 5th Uijeongbu axis.

For travellers on the SMRS, in-vehicle travel decreases 1.7%, from 44,770,031 to 44,020,325 passengers, while non-vehicle travel drops 1.4%, from 45,508,574 to 44,850,753 travellers.

Table 7-12. Link Flows by Mode in 4th Axis' Disruption

(unit : vehicles in road, passengers in SMRS)

Classification		Normal Situation			4th Namyangju Axis' Disruption		
		Link_AB	Link_BA	Total	Link_AB	Link_BA	Total
Road	Car	291,744,079	209,885,039	501,629,118	293,337,391	210,997,166	504,334,557
	Bus with Regular Route	22,404,305	19,101,618	41,505,923	22,404,305	19,101,618	41,505,923
	Other Bus	2,419,555	1,089,308	3,508,863	2,601,419	1,193,558	3,794,977
	Taxi	28,741,089	23,237,459	51,978,548	29,841,115	24,005,042	53,846,157
	Truck	63,247,958	36,967,090	100,215,048	63,215,913	36,905,977	100,121,891
	Subtotal of Road Traffic	408,556,986	290,280,514	698,837,500	411,400,143	292,203,361	703,603,504
SMRS	Non-vehicle Travel	22,604,575	22,903,999	45,508,574	22,271,219	22,579,534	44,850,753
	In-vehicle Travel	-	-	44,770,031	-	-	44,020,325
	Subtotal of SMRS Traffic	-	-	90,278,605	-	-	88,871,078

Table 7-13 shows that disruption of 4th Namyangju axis cause an increase of total TSTC to 5.77 billion KRW/day, a 1.6% increase, from 353.29 to 359.06 billion KRW/day. This value grows to 40.37 billion KRW/day where the disruption extends to one week. The road networks increase by 6.28 billion KRW/day, a 2.0% increase. The SMRS decreases by 1.2%, from 41.12 to 40.61 billion KRW/day, the smallest drop of the six axes.

Total TSTC from the travel time in road networks increases 2.8%, from 144.80 to 148.91 billion KRW during disruption. Operating costs of road networks increases TSTC by 1.54 billion KRW, and environmental impact costs of road networks produces a TSTC rise of 0.55 billion KRW. Parking factor made the least increase of TSTC to 0.01 billion KRW.

For the SMRS, non-vehicle travel time decreases 0.28%, from 16.42 to 16.14 billion KRW. The in vehicle travel time drops 0.2 billion KRW from 9.50 to 9.29 billion KRW, a 2.1% fall.

Table 7-13. Total Social Travel Cost caused by 4th Namyangju Disruption

(unit : billion KRW, %)

Classification		Total Social Travel Cost (TSTC)				
		Normal Situation	Disruptions in Namyangju Axis (4th)	Increace of TSTC/day	Rate of Increase	Increace of TSTC/week
Road	Travel Time	144.80	148.91	4.10	2.8%	28.71
	Operation	109.63	111.17	1.54	1.4%	10.75
	Traffic Accident	11.17	11.25	0.08	0.7%	0.57
	Environment	45.21	45.75	0.55	1.2%	3.83
	Parking	1.36	1.37	0.01	0.7%	0.07
	Subtotal of Road Traffic	312.17	318.45	6.28	2.0%	43.94
SMRS	Non-Vehicle Travel Time	16.42	16.14	-0.28	-1.7%	-1.95
	In Vehicle Travel Time	9.50	9.29	-0.20	-2.1%	-1.42
	Operation	15.21	15.18	-0.03	-0.2%	-0.20
	Subtotal of SMRS	41.12	40.61	-0.51	-1.2%	-3.57
Total Social Travel Cost (TSTC)		353.29	359.06	5.77	1.6%	40.37

(1million GBP ≒ 1.4 billion KRW, 2015 Budget of South Korea Government : 378 trillion KRW)

7.3.3 Integrated Vulnerability of 6th Goyang Transport Axis

Scenario 6 is the disruption of the 6th Goyang axis, when 17 stations are not available, from Daehwa Station to Gupabal Station of SMRS Line 3, the major commuting route from Goyang City to Seoul Metropolitan City. In addition, Gyeongui-Joongang Line connects both Paju City and Goyang City to the central Seoul. In this axis, the two railway networks go side by side, so that they are good alternatives when there is disruption on the SMRS. The section of SMRS Line 3 from Daehwa Station to Daegok Station is located in parallel with the section of Gyeongui-Joongang Line from Tanhyun Station to Daegok Station.

Road networks are: Seoul Ring Expressway (E100), 1st National Highway, 39th National Highway, 77th National Highway, and 2nd Jayuro Highway. Because Seoul Ring Expressway does not connect this transport axis to the central part of Seoul Metropolitan City, there is no expressway substantially within this axis. According to the Korean government's masterplan for expressways, the Seoul-Moonsan Expressway (E17) is planned to open in 2020, which will connect this area directly to Seoul.

Figure 7-17. Major Road Networks of 6th Goyang Axis

Source: http://map.naver.com/

Table 7-14 summarises the result of all link flows by transport mode in the 6th Goyang axis disruption. The total vehicles on all links is 705,947,895 during disruption, compared to 698,837,500 vehicles normally. This is a 1.0% increase. All the passengers who use SMRS decreases from 90,278,605 to 87,392,969 in the disruptive situation, a 3.2% decrease. These relatively small changes are directly related to the small change of TSTC, similar to the 4th Namyangju transport axis from the viewpoint of gross increase as well as increase per capita.

Other Bus increases 15.5%, from 3,508,863 to 4,051,987 vehicles. This increase is higher than that of the 4th Namyangju axis and lower than that of 3rd Seongnam axis. This is a pointer that explains the current bus service between satellite cities and Seoul Metropolitan City. In fact, there are many red-bus lines that support commuters on the 6th Goyang axis and 3rd Seongnam axis. In contrast, increasing is use of taxis is lower than the 4th Namyangju axis, at 2.6%, from 51,978,548 to 53,331,215 vehicles.

For travellers on the SMRS, in-vehicle travel drops 4.1%, from 44,770,031 to 42,920,510, while non-vehicle travel decreases 2.3% from 45,508,574 to 44,472,458.

Table 7-14. Link Flows by Mode in 6th Axis' Disruption

(unit : vehicles in road, passengers in SMRS)

Classification		Normal Situation			6th Goyang Axis' Disruption		
		Link_AB	Link_BA	Total	Link_AB	Link_BA	Total
Road	Car	291,744,079	209,885,039	501,629,118	294,948,273	211,970,382	506,918,654
	Bus with Regular Route	22,404,305	19,101,618	41,505,923	22,404,305	19,101,618	41,505,923
	Other Bus	2,419,555	1,089,308	3,508,863	2,763,450	1,288,537	4,051,987
	Taxi	28,741,089	23,237,459	51,978,548	29,569,021	23,762,194	53,331,215
	Truck	63,247,958	36,967,090	100,215,048	63,193,718	36,946,398	100,140,116
	Subtotal of Road Traffic	408,556,986	290,280,514	698,837,500	412,878,767	293,069,129	705,947,895
SMRS	Non-vehicle Travel	22,604,575	22,903,999	45,508,574	22,042,068	22,430,390	44,472,458
	In-vehicle Travel	-	-	44,770,031	-	-	42,920,510
	Subtotal of SMRS Traffic	-	-	90,278,605	-	-	87,392,969

Table 7-15 shows that disruption of 6th Goyang axis increases total TSTC to 6.38 billion KRW/day, a 1.8% increase, from 353.29 to 359.67 billion KRW/day. From the angle of the gross increase of TSTC, this axis ranked fourth, and third from the increase of TSTC per capita.

TSTC from travel time road networks increases 2.3%, from 312.17 to 319.46 billion KRW/day. Thi TSTC from travel time amounted to 64.4% of the entire increase of TSTC in road networks, or 4.68 billion KRW/day. In other words, traffic congestion and extended travel time, caused by disruption on the SMRS Line 3, was a major reason for increased TSTC, rather than the road traffic accident factor or environmental impact factor.

The SMRS experienced a 2.2% drop of total TSTC, from 41.12 to 40.21 billion KRW/day due to the decrease in its operating costs, as well as fewer travellers who board, leave, wait, and transfer. The decrease in in-vehicle travel was 5.6%, and that of non-vehicle travel was 2.2%.

Table 7-15. Total Social Travel Cost caused by 6th Goyang Disruption

(unit : billion KRW, %)

Classification		Total Social Travel Cost (TSTC)				
		Normal Situation	Disruptions in Goyang Axis (6th)	Increace of TSTC/day	Rate of Increase	Increace of TSTC/week
Road	Travel Time	144.80	149.49	4.68	3.2%	32.76
	Operation	109.63	111.46	1.83	1.7%	12.79
	Traffic Accident	11.17	11.27	0.11	0.9%	0.74
	Environment	45.21	45.86	0.66	1.5%	4.59
	Parking	1.36	1.38	0.02	1.5%	0.14
	Subtotal of Road Traffic	312.17	319.46	7.29	2.3%	51.02
SMRS	Non-Vehicle Travel Time	16.42	16.05	-0.36	-2.2%	-2.55
	In Vehicle Travel Time	9.50	8.96	-0.54	-5.6%	-3.75
	Operation	15.21	15.20	-0.01	-0.1%	-0.08
	Subtotal of SMRS	41.12	40.21	-0.91	-2.2%	-6.37
Total Social Travel Cost (TSTC)		353.29	359.67	6.38	1.8%	44.65

(1million GBP ≒ 1.4 billion KRW, 2015 Budget of South Korea Government : 378 trillion KRW)

2015 Budget of South Korea Government: 378 trillion KRW

7.4 Summary

The first section of this chapter described the scenarios of disruptive events on the SMRS for each transport axis in the SCA. Basically, the disrupted sections of the SMRS were chosen as the start station of each transport axis to the boundary between Seoul its satellite cities, considering the operational characteristics, and the goal of this research to identify vulnerability of transport networks along the six transport axes. If there is a different line of the SMRS close to the original line, that line may be a suitable alternative for travellers. Otherwise, they would move toward road networks to continue their trips using different transport modes: bus, car, taxi, and so on. Eventually, substitution for a specific line of the SMRS depends on the circumstances of the entire transport network and personal socio-economic situation.

The main focus then dealt with the integrated vulnerability assessment using the index of total social travel costs (TSTC) in each of the six transport axes. The analysis showed that TSTC of the SCA in the normal situation was 353.29 billion KRW daily. In the case of disruptions to the SMRS, the 1st Incheon axis was the most vulnerable to disruption, with an increase of 13.32 billion KRW of the TSTC, 3.8%. By contrast, problems on 5th Uijeongbu axis would trigger an increase of 5.11 billion KRW, the smallest of the six transport axes.

The 1st Incheon axis illustrated the highest preference for car travel among the six transport axes and the lowest preference for bus as an alternative mode, and high intention to use other SMRS services. These features can be explained by well-connected road networks and the SMRS within the 1st Incheon transport axis. In order to decrease the impact of disruption on the SMRS, metro bus service can be enhanced from Incheon corridor to Seoul Metropolitan City directly. Exclusive bus lanes may be an effective ways to induce travellers to transfer from car to bus. If job opportunity is supplied sufficiently in the Incheon corridor, commuting travel demand would be reduced and the TSTC could decrease where there was an SMRS disruption.

Chapter 8 Strategy to Increase the Resilience of Transport Networks

The previous chapter identified the integrated vulnerability of transport networks in the SCA through the analysis of TSTC in both a normal situation and a disrupted situation, following 6 scenarios of disruptive events on the SMRS. However, preventing a disruptive event on the SMRS, and decreasing the impact of a disruption on transport networks, are as important as the assessment of the integrated vulnerability of transport networks. In this chapter, strategies to increase the resilience of transport networks in the SCA were suggested by experts through interviews undertaken in Korea from January to February 2017.

8.1 Introduction

8.1.1 Expert Interview as a Qualitative Research Method

Qualitative research focuses on using texts rather than numbers and consists mainly of open-ended questions rather than closed questions. The process includes setting up questions, collecting data through research activity, and data analysis inductively building from the particular to general themes. Most data for the qualitative research method is composed of texts, (Creswell, 2013).

Most recoverable information about human thought and behaviour is verbal and examples are: books, newspapers, magazines, scripts of interviews, and so on. Bernard (2012) classified text analysis methods into hermeneutics (interpretive analysis), narrative analysis, discourse analysis, the grounded theory approach, and content analysis. Hermeneutics originated in Bible commentary and has been extended to the social sciences. Narrative analysis aims to identify regularities when people tell stories or give speeches. Discourse analysis involves interactions among people such as physician-patient encounters (Bernard, 2012).

One of the most referenced approaches for qualitative research method is grounded theory (Glaser and Strauss, 1966). It was then called the constant comparative method, but later became known as the grounded theory method. It is an inductive research method that first analyses fundamental data that are written in texts or recorded in scripts, from which general ideas are induced such as concepts, categories, and theories (Bernard, 2012). The first process can be defined as coding, which is a procedure to identify principal contents of original texts; most coding asks analysts to read the data and demarcate segments within it. “When coding is complete, the analyst prepares reports using a mix of: summarising the prevalence of codes, discussing similarities and differences in related codes across distinct original sources/contexts, and comparing the relationship between one or more codes (Shirish, 2013, p.31).

This work has adopted expert interviews as a way of acquiring the fundamental data on management strategies for more resilient transport networks in the SCA.

8.1.2 Questionnaire for Expert Interviews

The interviews were primarily aimed at eliciting experts' opinions on these three themes:

- evaluation of current transport networks in the SCA,
- assessment of current measures to mitigate disruptive events on the SMRS,
- how to enhance responses to disruptions on the SMRS and create more resilient transport networks in the SCA.

In the first section of the Questionnaire, the questions were related to the evaluation of current transport networks across the six transport axes. In the event of a disruption to the SMRS, as with the scenarios of paragraph 7.1, estimates of vulnerability for each transport axis were required.

The second section of the Questionnaire focused on the current measures to mitigate disruptive events by government, by operators of the SMRS, by users of the SMRS, and by mass media including the Internet. Interviewees were asked to assess the main problems within government organisations and different SMRS operators. Shortcomings of mass media were also requested concerning information delivery by broadcasters and newspapers.

The last section of the Questionnaire addressed minimising the impact of disruptive events on the SMRS. Strategies from expert groups were elicited for the following: providing travellers with alternative transport modes, disseminating information of disruptive events to travellers or potential users of the SMRS, preparing urgent repair equipment or facilities and management systems by operators of the SMRS, and strengthening transport networks by infrastructure investment following a long-term plan.

Appendix 3 shows the full version of questionnaire for the interviews with experts.

8.1.3 Interviews with Experts

To get diverse ideas of strategies, expert interviews were conducted as shown in Table 8-1. The interviews were undertaken face-to-face in January and February 2017. Two additional experts took part through paper-based questionnaires. Interviewees were recruited in three categories: government authorities, SMRS operators, and senior academic researchers. Two participants came from central government organisations and three from local government. Three participants came from public operators and two private operators of the SMRS. Four professors and five researchers took part. In total there were 19 experts.

Table 8-1. List of Expert Interviewees

No.	Position	Oranization	Classification	Date
1	Director, Deputy Director	Ministry of Land, Infrastructure and Transport	Central Government	31st Jan 2017
2	Dietctor	Ministry of Public Safety and Security	Central Government	26th Jan 2017
3	Team Leader	Seoul Metropolitan City	Local Government	3rd Feb 2017
4	Team Leader	Incheon Metropolitan City	Local Government	1st Feb 2017
5	Team Leader	Gyeonggi Province	Local Government	2nd Feb 2017
6	Director	Korea Railway Corp. (KORAIL)	Public Operator	31st Jan 2017
7	Director	Seoul Metro	Public Operator	1st Feb 2017
8	Assistant Team Leader	Incheon Transit Corp.	Public Operator	1st Feb 2017
9	Chief Operation Officer	Neo Trans Company for DX Line	Private Operator	3rd Feb 2017
10	Chief Director	Airport Railroad Company	Private Operator	25th Jan 2017
11	Professor	Hanyang University	University	3rd Feb 2017
12	Professor	Yonsei University	University	2nd Feb 2017
13	Associate Professor	Korea National University of Transportion	University	25th Jan 2017
14	Professor	Ajou University	University	25th Jan 2017
15	Chief Director	The Korea Transport Institute	Research Institute	26th Jan 2017
16	Research Fellow	The Seoul Institute	Research Institute	3rd Feb 2017
17	Research Fellow	Gyeonggi Research Institute	Research Institute	2nd Feb 2017
18	Research Fellow	The Incheon Development Institute	Research Institute	Paper Interview
19	Research Fellow	The Korea Transport Institute	Research Institute	Paper Interview

8.1.4 Coding the Result of Expert Interviews

Result of expert interviews were firstly coded by keywords. There were 19 expert interviewees and the numbers of below is the same in the Table 8-1.

1. GTX project, passing track, economic feasibility vs. safety investment, disseminating disruptive events information, different assessment between functional facilities and safety facilities, redundant facilities for emergency situation.

2. coordinating government organization, role of local government, cooperation between local government and central government, CBS (Cell Broadcasting System), costs of CBS service, decision making when CBS to be used, disseminating disruptive events information to all people vs. people who need it, privacy vs. publicity.

3. different vulnerability according to each transport axis, reciprocal function between bus and railway networks, supplying chartered bus in a disrupted SMRS section, cooperation between operators and local government, application for information sharing, providing alternative transport modes information within stations of SMRS, investment for outdated trains.

4,8. operating bus as well as railway networks, focus on recovering normal service vs. transporting passengers with alternative modes, cooperation among operators, cooperation between operators and local government and central government, providing information within train stations, passing track, feasibility study focused on economic benefits and costs, metropolitan transport organization, cooperation between operators and local government.

5,17. prohibiting standing passengers in metro bus, shift system of taxi service, substantial metropolitan transport authority in the SCA, Gyeonggi bus television, VMS on bus stops, bus rapid transit and tram service as alternative transport modes.

6. how to deliver information to passengers, internal broadcasting with/without electricity supply, train driver, train staff to help train driver, passing track, towing train for broken trains, alternative transport modes, including safety facilities in the design stage, cooperating among operators.

7. broadcasting within trains, station staffs, passing track according to section of railway networks, budget for safety investment, free riding for senior citizens, insufficient time for inspection, train drivers and supplementary staff, safety facilities.

9. complimentary location for existent railway networks, connecting cities with long space between stations, competition between BRT service and railway networks, unmanned operation of trains, railway sharing for both direction trains, cooperation between operators and government, mass media, safety investment not considering economic feasibility.

10. alternative transport modes, cooperation among operators, accessibility to Incheon International Airport, emergency task force team, emergency manual, train driver's announcement, notice by the Internet and mass media, cooperation from passengers, disruption information for foreigners, mobile application as an information platform.

11. different situation for alternative transport modes and routes, concentration of transport infrastructure for a few specific transport axes, inefficiency of railway operation because of different operators of the SMRS, effectiveness of emergency manual, passing track, providing information to all people vs. privacy problem, passengers' location information through their mobile phones, disadvantage of economic feasibility, classification safety facilities according to their priorities, relationship between travelling pattern and change of transport networks in a short and long term, critical path of entire transport networks in the SCA, metropolitan transport authorities.

12. equity analysis, mobility analysis, regional inequality, passing track, feasibility study based on economic criteria, priority on safety investment, dissemination of disruptive events on the SMRS.

13. 3rd Seongnam axis, 5th Uijeongbu axis, 2nd Suwon axis, few measures for providing passengers with information, emergency plan considering location of disruptive event and condition of facilities, cooperation among operators, disseminating quickly disruption information, no information of alternative transport modes, application for disruptive situation, administrative organization for Seoul Capital Area, cooperation between railway operators and bus operators, public operation of bus, direct notice from passengers, passing track, low economic feasibility for safety investment.

14. critical path, focus on facility recovery, no guidance to travellers how to react, alternative transport mode, information, smart phone, application, real time update of disruptive events, CBS, text, Kacao Talk, emergency shuttle plan, road construction as detour plan, passenger dispersion, emergency manual according to each station, reinforcing weaker section of transport networks.

15. isolation rate, grading methods for rail operators, report process to higher decision-makers, what is to be mainly broadcasted, guideline for passengers' response to disruptive events, economic feasibility vs. safety investment, incentive for bus operators' cooperation, disseminating information, safety tax, safety education in primary and secondary schools,

16. unbalanced infrastructure in the SCA, cooperation among operators, empowerment from government to operators of railway networks, instruction for passengers in a disruptive situation, disseminating information through mobile phones, equal distribution of alternative transport modes within the SCA.

18. cooperation among operators, responsibility of local/ central government, providing information of alternative transport modes, suspending shift system of taxi service, additional supply of chartered bus, safety manpower, expanding bus rapid transit.

19. cooperation among operators, coordination between different operators, integrating bus operators and railway operators, preparation of facilities, manpower for the disruptive situations, delivering information of alternative transport modes by mass media, integrating emergency measure organization.

8.1.5 Strategies for More Resilient Transport Networks

Strategies for more resilient transport networks were categorised into: measures that should be done when disruptive events on the SMRS occur, preparation of items for future disruptive events, and long-term plan to strengthen transport networks. These strategies were induced by codes in section 8.1.4.

The first category of strategies for transport networks to minimise the impact of disruptions on the SMRS can be how to solve effectively an extraordinary situation when a disruptive event on the SMRS occurs suddenly. When disruptive events happen unexpectedly, normal operation cannot be provided. An operator of the disrupted line has to recover the suspended operation of the line as soon as possible. Government authorities can provide travellers with emergency transportation tools by revising the current transit service route or by chartering additional buses. Mass media and the Internet can propagate the disruption information to travellers or potential passengers. Cooperation among operators of the related SMRS lines is required to reduce the impact.

Table 8-2. First Category of Strategies for More Resilient Transport Networks

Strategies	Interviewee who suggested their opinions
Swift recovery from disruptive events	10, 13, 14
Providing alternative transport modes	3, 4, 8, 9, 14,15, 18, 19
Propagating information to travellers	2, 3, 5, 6, 7, 8, 9, 10, 11, 13, 14, 16, 19
Cooperation among SMRS operators	2, 5, 8, 10, 11, 13, 15, 16, 18, 19

Secondly, the category of strategies for transport networks to decrease the influence of disruptions on the SMRS is by preventing disruptive events themselves on the SMRS. In other words, the lower the possibility of disruptive events, the more stable is the SMRS. In particular, if rescue routes and cross passages of railways are considered during the preliminary stage of facility design, the impact of later disruptions on the SMRS can be minimised. In addition, regular inspection of trains, railways, and other facilities of the SMRS, can reduce the probability of disruptive events. Furthermore, operators must have emergency response procedures in place according to the types and location of disruptions. Travellers can respond more effectively to an emergency situation with appropriate safety education. Well-linked multimodal transfer systems within the SMRS can also reduce the level of impact of disruptions to the SMRS.

Table 8-3. Second Category of Strategies for More Resilient Transport Networks

Strategies	Interviewee who suggested their opinions
Investment in mechanical facilities within the SMRS	1, 2, 6, 7, 8, 9, 13, 14, 16, 19
Inspection of trains, railways, and other facilities	7, 16, 19

Strategies	Interviewee who suggested their opinions
Emergency response manuals by type and location of disruption	11, 13, 14, 15, 18
Safety education	15, 16
Operation of multimodal transfer systems within the SMRS	13

The third category of strategies for transport networks to reduce the effect of disruptions on the SMRS is strengthening transport networks in the SCA by infrastructure planning and construction in the long-term. This strategy assumes that having many alternative routes or transport modes can reduce the impact of disruptive events on the SMRS. Therefore, constructing alternative railways or roads in a vulnerable region can strengthen transport networks. In this context, a safety tax can be an effective way to secure proper budgets for the investment in safety measures. On the other hand, safety criteria should be adequately considered during the feasibility assessment within constrained infrastructure investment budgets. Additionally, an integrated transport authority for the SCA region would be able to utilise optimal facilities to resolve a disruptive event on the SMRS. Finally, according to the result of vulnerability assessment of each transport axis, new transport infrastructures need to be constructed as well as optimising the current transport networks.

Table 8-4. Third Category of Strategies for More Resilient Transport Networks

Strategies	Interviewee who suggested their opinions
Safety tax	15
Safety criteria during the feasibility assessment	1, 2, 8, 11, 12, 13, 15, 16, 19
New transport authority for the SCA	4, 5, 11, 13, 17, 18, 19
Investment for additional transport infrastructure projects	5, 8, 14, 18, 19

8.2 Strategies to Solve Disruptive Events

8.2.1 Propagating Information to Travellers

This was mentioned by 13 experts.

One of the important issues for the disrupted SMRS is the sudden decrease of public transport supply and unsatisfied travel demand in the local area. One of the reasons for the gap between decreased transport supply and unsatisfied travel demand may be a lack of information regarding disruptive events on the SMRS. In this section, some tools are suggested that will increase dissemination of information during the disrupted situation.

Earlier, it was recognised that travellers most wanted to use the Internet as a source of information on a disruption. Their second favourite tool was mass media, followed by a notice from government. Social networks were not as popular as other information sources. Over 77% of all South Koreans are smart phone users, which indicates an efficient method to propagate information on disruptive events.

Internet service provided by mobile phone can be the most efficient tool for disseminating information. While travelling, most Koreans browse Internet portals with their smartphone. Frequently used portals are Naver (www.naver.com) and Daum (www.daum.net). If these portals can display information on disruptive events right after the disruption occurs, it would be a good way to disseminate the situations quickly and simultaneously. The operators of the SMRS will need to contract with the portal companies to display a notice of disruption when requested by the operators.

Another useful method is a mobile application that delivers transport information, such as the operation schedules of all SMRS lines, transfer information within the SMRS or onto different transport modes. Naver Map and Daum Map provide a service for travellers to search for an optimal path from a specific origin to a given destination in Korea, including total travel time and travel cost across diverse modes and routes. However, this information is limited to normal travelling conditions. Disrupted events are not reflected directly, even though a suspended part of the SMRS may impact on availability of a section of the SMRS and strongly influence travel time. Therefore, it is desirable for major navigation applications to reflect disruptive events swiftly, when they receive notice from the SMRS operators.

In addition, CBS can be useful to disseminate information on a disrupted situation, similar to sending a disaster message through CBS. As mentioned in section 4.5.2, CBS has been implemented free as tele-communication companies' social contribution, with no additional cost for the government and mobile phone users. A characteristic is that a CBS message can be delivered simultaneously by the government to all mobile phone users within a selected area. Another advantage of CBS is that it is independent of type of mobile phone or smart phone.

Bus TV and BIS, bus information system, are available for bus passengers who plan to transfer to the SMRS. All buses in Seoul Metropolitan City, Incheon Metropolitan City, and Gyeonggi Province, have bus TV inside so that bus passengers can watch it. This system allows bus passengers to get news about disruptive events on the SMRS. Travellers at bus stops can also acquire the same news through the variable message sign (VMS), which is a part of bus information system in the SCA. Figure 8-1 shows the Bus TV and VMS at a bus stop.

Figure 8-1. Bus TV (left) and VMS on Bus Information System (right)

Source: google (adapted, 2017)

According to the online survey, about 30% of respondents said that they preferred mass media to get information on disruptive events. Currently, mass media focuses on sensational scenes of abnormal situations rather than delivering useful information to travellers, such as alternative modes or routes. It is hoped that the mass media can be persuaded to convey realistic solutions to travellers when abnormal situations happen within transport networks in the SCA. Of course, mass media must be provided with the fundamental information about disruptive events by the SMRS operators.

8.2.2 Cooperation among Operators of the SMRS

This was mentioned by 10 experts.

The SMRS has 11 operators in charge of 18 separate lines, covering 1,014.4 km and operating 636 stations within the SCA. Although each operator is in charge of a specific section, passengers may travel across sections that are managed by different operators. When there is a disruption on a specific section, other operators could fail to respond to the situation as they only have an indirect responsibility. Furthermore, there may be barriers to cooperation between different operators to obtain the right equipment to resolve a disruption.

A common operator in charge of the whole of the SMRS might be an ideal organisation to solve a non-standard situation, and could minimise the impact of that disruption. Of course, the owners of PPP (public-private partnership) projects for a few lines, and public operators of the SMRS, may be motivated by different interests, and it is difficult to consider a consolidation in reality. However, integration between different public operators is a feasible target to increase efficiency and introduce an economy of scale.

8.2.3 Providing Alternative Transport Modes

This was mentioned by 8 experts.

While the disrupted railway network is being recovered, it is desirable for passengers to have alternatives to continue their original trips or adjust their routes or initial modes. However, it is impossible to predict where an event would occur. If railway networks operators also controlled other public transit modes such as buses, they would have the potential to provide passengers with detouring modes from a disabled section of the SMRS. They could directly respond to disruptions on the SMRS. However, of the 11 SMRS operators, only Incheon Transit Corporation operates road transit and Incheon Metro Line 1 and Incheon Metro Line 2. In other words, most operators cannot immediately supply any substitutes for disrupted railways services.

Therefore, it devolves upon local government to be responsible for the major role in allocating emergency transport modes to help passengers who need alternatives in a crisis. The local governments in the SCA are Seoul Metropolitan City, Incheon Metropolitan City, and Gyeonggi Province. Each local government has authority to approve an operation plan for public transit and adjust its schedules.

What should local government do in order to provide travellers with different solutions? First, local government must link scheduled bus routes with principal subway stations such as transfer stations. Scheduled bus routes have more flexibility in connecting stations of the SMRS and should provide a complementary function when a section of the SMRS is disrupted. Local government could have contracts with private bus owners to acquire chartered buses in emergency situations. Buses provided by public institutions for their commuting staff can also be utilised for alternative modes. During disruption, demand for taxis can increase. The temporary lifting of the shift system for taxis would be another method to increase alternative transport modes.

When local government is planning to supply alternative transport modes in an emergency situation, passengers' criteria for changing to alternative modes in a long duration disruption must be taken into account (see Table 6-21). 50.9% of travellers selected total travel time as their first criterion. Total monetary cost was chosen by 26.1%, while 15.3% said that reliability of travel time was important. Comfort during travel was supported by 6.4% of the respondents.

Travellers, especially commuters, were most sensitive to the total travel time. Consequently, they expected local government to provide them with alternative transport modes that could be operated within plausible travel time, particularly in the morning peak hours and evening peak hours. Therefore, alternative transport modes need to be selected by considering how to minimise total travel time during a long disruption of the SMRS. From this viewpoint, using bus rapid transit and connecting different lines of the SMRS should be prioritised by local government.

8.2.4 Recovering Swiftly from Disruptions on the SMRS

This was mentioned by 3 experts.

All railway authorities in Korea must have their own emergency guidelines to react to disruptive events, according to the Railway Safety Act of Korea and the general guidelines for emergency measures from the Ministry of Land, Infrastructure, and Transport (MOLIT). When disruptive events occur on the SMRS, the guideline states that priorities for recovery are: saving passengers and safety measures, reopening the main railway, protecting properties of the SMRS, and assets of private parties (KORAIL, 2013). Types of disaster on railway networks are classified as: collision, derailment, fire, explosion, and flood. Accident location is categorised by station, tunnel, bridge, level crossing. Objects of accident are classified as: passenger train, freight train, dangerous goods transport train, buildings, and other facilities (MLTM, 2009). From the perspective of recovery of operations, reopening the main railway is the crucial component when a railway operator responds to a disruptive situation.

In order to recover swiftly from disruptions on the SMRS, essential elements are: dispatching the emergency team, acquiring emergency materials for accident recovery, and preparing rescue equipment. Furthermore, a cooperation system with related organisations, and inspection of equipment and materials for restoration, are fundamental requirements.

8.3 Strategies to Minimise Impact of Disruptions

8.3.1 Investment for Facilities of the SMRS

This was mentioned by 10 experts.

When a train breaks down, it is difficult to remove quickly because it is on fixed rails and has preceding/following trains. Furthermore, railways normally operate on the principle of cross running. Therefore, a train that is unable to move by its own power can be a substantial obstacle to the entire operation. As a result, all trains in both directions on a specific section of the SMRS may be suspended due to a train that is out of order on a particular section. For instance, on 3/04/2014 the derailment of a train at Samgakji station on SMRS line 4 closed 8 stations from Seoul Station to Sadang Station in both directions for five hours (See Table 3-12).

Passing track and refuge tracks can be an effective solution to the above problem. Passing track can minimise the impact of the faulty train on a particular section by letting the other trains detour by the disrupted section. However, the concept of passing track was not considered when the SMRS Line 1 was designed and constructed in the mid-1970s. The situation of SMRS Line 1 is very similar to that of Seoul Metro Lines 2, 5, 6, 7, 8 and SMRS Lines 3 and 4. SMRS Line 1 to Seoul Metro Line 8 were financed publically and have been operating since the 1980s.

In contrast, the privately financed Seoul Metro Line 9 and Shin Boondang Line were designed and constructed in the 2000s. In particular, on Seoul Metro Line 9 passing track was originally conceived as an alternate operation for an express train and a general train. The operator of this line can minimise unavailable stations when there is a disruptive event. The Shin Boondang Line was constructed and operates automatically without a driver. This line has several refuge tracks to receive faulty trains during operation.

In conclusion, passing track or refuge track should be included whenever a new railway line is constructed in order to minimise the impact of a disruption to part of the SMRS. Moreover, passing track or refuge track should be added to current lines where possible, depending on the probability of disruption to each section of the SMRS. Of course, the number of passing tracks or refuge tracks should be determined by criteria of safety, economic feasibility, and topological function.

8.3.2 Emergency Response Manuals by Type and Location of Disruptions

This was mentioned by 5 experts.

Emergency response manuals are focused on the operators' actions in the event of disruption to the SMRS. The manuals have to be prepared by types of disruption and by location of disruptions. Currently, emergency response manuals for all SMRS operators are based on the standard emergency response manual for urban train accident from the MOLIT (MOLIT, 2014). MOLIT has authority to approve the emergency response manuals for all SMRS operators according to Article 34-6 of the Framework Act on The Management of Disasters and Safety.

The MOLIT standard classifies disasters on urban train networks into: collision, derailment, fire, explosion, and flood. And the importance of a disruptive event is categorised as: attention, caution, alert, and serious (MOLIT, 2014; MPSS, 2015). Therefore, each emergency response manual for all SMRS operators basically follows these four levels for each of the five types of disaster.

However, neither the MOLIT standard nor the operator’s manual cover the location of a disaster. Each line of the SMRS covers a wide area in the SCA, and the action plan to address a disruptive event may need to differ depending on the location of the disruption. Resources available can vary with different distances from major stations, train bases, refuge track, and recovery material storage. Therefore, after determining current storage of recovery material, the information should be shared with and utilised by different SMRS operators. Although normal operation of each line of the SMRS is divided into different organisations, emergency response should be executed by a cooperative of the different SMRS operators. Local governments and the MOLIT must revise the standard emergency response manual so that scenarios are established according to the regional location of disasters.

8.3.3 Inspection of Trains, Railways and Other Facilities

This was mentioned by 3 experts.

In an ideal world there would be no disruptive events on the SMRS. However, minimising the occurrence of abnormal status is a realistic goal as an operation strategy. Scrutiny of facilities normally means that trains, railways, stations, electric plant, and other facilities are under daily examination.

The working schedule for the SMRS on weekdays is 05.00 to 01.00 the next day. The weekends’ schedule is normally shortened about 1 hour at both ends (06.00-24.00). Therefore, out-of-hours inspection time is very limited, from around 1.30 am to around 4.30 am, about 3 hours a day. This is the same all the year round. Shortage of examining time may increase the probability of structural faults on the SMRS.

Current SMRS schedules have no space for a full check-up of railways, electric plant, and signalling systems. There should be a day allocated periodically off-operation for an in-depth inspection, by turns among different lines of the SRMS. Such an off-operation day could be set for during weekends, when passenger traffic is less.

8.3.4 Safety Education

This was mentioned by 2 experts.

Drivers of trains and station employees are responsible for the emergency when a disruptive event first occurs. However, it is very difficult to control circumstances because there will be many confused passengers who want to escape the situation as soon as possible. In other words, passengers should have been previously instructed on how to react properly to a serious disruption.

Safety education has usually focused on what train drivers have to do and how station staff should respond in an emergency situation, rather than the main guidance for passengers in unusual events. It would be helpful for passengers to know their appropriate procedures in case of derailment, collision, fire, and explosion. It is essential for passengers to distinguish what they should do, what they can do, and what they should not do, during an emergency. Given more than 1,000 travellers per carriage, in a rake of 10 carriages, the few train staff cannot efficiently evacuate all the passengers who have not been taught about emergency situations.

Video screens inside trains might be an effective method to deliver guidance to passengers (assuming power is still available). Travellers using the SMRS on normal days can be instructed naturally how to react to an extraordinary environment and cooperate with train staff. Instructions on the wall inside the train can also be used to disseminate the information regarding evacuation. Spaces by the doors have an advantage in displaying instructions on emergency action. In addition, passengers can use leaflets provided by government or SMRS operators for just such an occasion.

8.3.5 Operation of Multimodal Transfer Systems within the SMRS

This was mentioned by 1 expert.

Providing travellers with well-connected multimodal transfer systems aims at solving problems by alternative transport modes during disruption.

Bus is a major alternative mode of public transport when operation of the SMRS is suspended. On average, 32.3% of travellers said that they would use bus as an alternative mode (see Table 6-1). Scheduled bus networks must be highly coordinated with the main stations of each the SMRS line. Information on scheduled buses should be available inside stations for transfer or alternative use. Chartered buses can underspin the scheduled bus service networks by transporting travellers from the starting station of the disrupted section to the next available station or even the destination station. It would be better for SMRS operators or governments to retain several buses so that they can supply these directly in the event of a disruption. In normal times, these buses could be used for commuting by their employees or as a social welfare service for the disabled.

Another important facility to minimise the impact from a disruption is extra car parking near major stations of the SMRS. On average, 27.2% of travellers chose car for an emergency situation. If these travellers drove their own car from home to their workplace, TSTC would increase greatly from operating costs, road traffic accidents costs, and environmental impact costs. The provision of sufficient space for extra car parking near stations could induce travellers toward a working section of the SMRS. Undoubtedly, such a car parking facility is also useful on a normal day to encourage travellers to move from road networks to the SMRS.

8.4 Long-term Strategies to Strengthen Transport Networks in the SCA

8.4.1 Safety Criteria during the Feasibility Assessment

This was mentioned by 9 experts.

The criteria for the preliminary feasibility study have been: economic feasibility, environmental impact, and balanced regional development (KDI, 2016). Although road traffic accident reduction is mentioned in the process of economic feasibility analysis, ancillary design items have a tendency to be excluded because they increase the total project costs. Even a newly planned railway project is likely to omit refuge tracks to minimise total project costs and enhance economic feasibility. In the current criteria for feasibility study to assess new infrastructure projects, the safety category must be added.

Safety criteria during the feasibility assessment are strongly linked to a separated budget system for safety administration. A fundamental paradigm shift for safety is the Safety Special Account in the government budget, so that safety-related administration can be addressed independently of economic benefit-cost ratios. Therefore, a safety tax may be a crucial element for the separate safety budget account, which produces different criteria to make a safer environment.

8.4.2 New Transport Authority in the SCA

This was mentioned by 7 experts.

Three metropolitan cities are found within the SCA, where more than 25 million people live. The total length of the SMRS is 1014.4 km, which has 636 stations and 11 operators. More than 10 million commuters travel daily in the SCA, see Table 3-6. These facts suggest an integrated administrative organisation to solve transport problems efficiently in the SCA.

The Metropolitan Transportation Authority (MTA) was created in 2005 with the approval of central government and has enabled cooperation between Seoul Metropolitan City, Incheon Metropolitan City, and Gyeonggi Province. All MTA employees are taken from the three local governments, and its budget shared among them. The MTA chairperson has the rank of Director-General, lower than Vice-Mayor or Vice-Governor. The MTA has not been active in solving problems within the SCA, but has only collected current traffic information. It does not want to take the initiative when it comes to the transportation problems in the SCA.

Therefore, the suggestion is that there should be a substantial organisation that is independent of the three local governments. A special Act needs to be enacted to grant the new transport authority legal status. Independent personnel rights and self-governing revenue and budget planning are essential factors so that the new transport authority for the SCA is involved with transport issues around the SCA, including response to emergencies on the SMRS.

8.4.3 Investment for Additional Transport Infrastructure Projects

This was mentioned by 5 experts.

The 1st Incheon axis produces the largest increase of total TSTC when there is a disruptive event on SMRS Line 1, while the 5th Uijeongbu axis was the most vulnerable axis from the perspective of TSTC per capita (see Table 7-2). When local or central government currently decides the priority for a new infrastructure project, vulnerability of local transport networks is not considered at all. Cost-Benefit analysis for the target project has been a crucial factor in determine the project implementation (KDI, 2015). Because of low probability of a disruptive event and its unpredictability, vulnerability assessment tends to be seen as unimportant.

It seems that there is a full connection between road networks and railway networks when government makes a masterplan for both transport networks. However, economic feasibility has dominated vulnerability of transport networks, or connectivity of entire networks, when the implementation is chosen. Advanced research certainly suggests that a base level of vulnerability of transport networks should be adopted. Thus the government should choose target projects preferentially to satisfy the minimum level of vulnerability of transport networks around all transport axes within the SCA.

To increase the resilience of transport networks in the SCA, the Metropolitan Express Railway (MER) project would be a remarkable alternative to a disruptive event on the current SMRS. As mentioned in section 3.2, the MER project has been planned to operate with an average speed of 100 km/h at a depth of 50 m. Most of all, the three lines of the MER project connect five transport axes directly to the centre of Seoul Metropolitan City with deep underground tunnels so that it overcomes interruptions of the current SMRS due to extreme weather conditions such as heavy snowfall, floods or landslides.

8.4.4 Safety Tax

This was mentioned by 1 expert.

The Korea Transport Institute (KOTI) surveyed 1,014 people's consciousness of safety six months following the *Sewol Ferry Disaster* on 16 April 2014. The result revealed that the majority of Koreans wanted the government to protect people from various disasters without any tax increase or escalation of public transit fares. 70.4% of participants responded negatively to the adoption of a safety tax, while 68.6% were against an increase of public transit fares (KOTI, 2014).

Lee (2014) analysed the reasons why people are reluctant to accept safety costs along with becoming active participants in promoting safety culture. He found that people thought the probability of encountering disasters was very low and that disasters had not much to do with them directly. They also believed that tax paid to the government was not used to benefit their safety. Also, there was a feeling of being dependent on government during disasters rather than doing something actively to help others.

He goes on to say, "it is urgent for people to recognise that safety is not free" (Lee, 2014, p.25). Government can do better to secure safety when there is sufficient budget. A safety tax is a good example of providing for a safety budget, and it makes government concentrate on safety administration. When the safety budget is consolidated with general demand, economic feasibility dominates selection criteria and priority for safety-related projects would lose its competitiveness.

Also important is that people have to understand their own responsibility as well as the role of government during unexpected disasters. Following safety guidelines should be taken for granted, although it might be uncomfortable. The more invested in safety, the safer circumstances become (OECD, 2014).

8.5 Summary

This chapter suggested management strategies to increase the resilience of transport networks, supported by 19 experts taken from government officials, staff of SMRS operators, and researchers in transport networks. Coding from the experts interviews suggested three categories of management strategies: to solve disruptions on the SRMS efficiently, to minimize the impact of disruptions, and long term policies to strengthen the transport networks in the SCA.

The first category of strategies for transport networks to minimise the impact of disruptions on the SMRS can be how to solve effectively an extraordinary situation when a disruptive event on the SMRS occurs suddenly. When disruptive events happen unexpectedly, normal operation cannot be provided. The experts claimed that propagating information about a disruption was the most important factor. Quick recovery from the disruptive event is crucial to reduce the impacts by the operators of the SMRS. Government authorities need to be prepared to provide travellers with alternative modes like chartering additional buses. Mass media and the Internet can mitigate the situation by propagating the disruption information to travellers or potential passengers.

The second strategy was related to minimise the impact of disruptions on the SMRS, including investment in facilities for the SMRS, emergency response manuals, safety education, and so on. This strategy focused on how to reduce the probability of the disruptions and to minimize the impact of abnormalities. If rescue routes and passing track of railways are considered during the preliminary stage of facility design, the impact of later disruptions on the SMRS can be minimised. In addition, regular inspection of trains, railways, and other facilities of the SMRS, can reduce the probability of disruptive events. Operators can also reduce the impact by preparing emergency response procedures according to the types and location of disruptions.

The third strategy dealt with several ideas to strengthen transport networks of the SCA in the long term plan such as constructing alternative railways or roads in a vulnerable region. This strategy is strongly related to the investment on the transport infrastructures. In this context, a safety tax can be an effective way to secure proper budgets for the investment in safety measures. Another important agenda is to adopt safety criteria during the feasibility assessment for the transport infrastructure. Integrated transport authority for the SCA region, which can coordinate the transport issues in the SCA substantially, should be founded so that the authority can utilise optimal facilities to resolve a disruptive event on the SMRS.

Chapter 9 Conclusion

9.1 Main Conclusions

Transport networks such as road, railway, and subway are crucial elements for both daily life as well as economic activity. Government services are also crucially dependent on the connectivity of major infrastructure. Since transport networks are open for general access and have fixed locations, they are quite vulnerable to deliberate attacks and natural disasters. Because of the complexity and connectivity of transport networks, they are sensitive to incidents that vary in scale and cause. Therefore, it is important to assess the vulnerability of transport networks and strengthen relatively weak sections of the transport networks.

The use of public transport is more likely to be affected by reduced serviceability than travelling by private car, when considering flexibility of changes to an original trip plan. Further, when there is a disruptive event on a specific section of a transport network, the range of railway networks affected is wider than that of road networks. Consequently, it is essential to assess the vulnerability of public transport networks.

However, vulnerability assessment of public transport networks, such as the Seoul Metropolitan Railway Systems (SMRS), cannot be properly carried out without considering adjacent road networks. Although some travellers would cancel or postpone their original trips because of the unavailability of a section of the SMRS, most travellers who cannot use a specific subway line would continue their journey by taking a bus and a taxi or driving their own cars. They could also modify their normal route on the SMRS in order to bypass the unavailable section, being partially supported by several transport modes on road networks. It is therefore important to identify the impact of a disruptive event not only on the SMRS, but also on the adjacent road networks.

It is also important to identify the weakest and the strongest transport axis among the six axes in the SCA, from its vulnerability to disruptive events. The current criteria for infrastructure investment do not reflect the vulnerability of transport networks, which differ according to the transport axis. Vulnerability of transport networks may not relate significantly to the population of the target region. It is thus useful to identify the most vulnerable axis from a viewpoint different to the economic feasibility analysis.

In addition, while appraising vulnerability, it is necessary to take into account personal intentions for alternative transport modes and routes during specific disruptive events. When a disruption occurs, personal attitudes are very different to those during normal circumstances, so that choices made may not truly reflect individuals' mode choice and route selection. Since it is rare for travellers to experience an extreme incident, the data revealed does not properly explain travellers' choices in those situations. As a result, stated intentions need to be gathered so that the desires of travellers can be analysed.

Finally, it is necessary to establish management strategies that will increase the resilience of the transport networks in the SCA and suggest guidelines for users during a disruption. Their purpose is to reduce the number of disruptive events on the SMRS and to minimise the impact when disruptions do occur. Given such strategies, local and national governments can strengthen relatively weak areas so that the decreased serviceability of transport networks is minimised. SMRS operators can enhance their ability to respond with well-prepared equipment and trained human resources.

9.1.1 Integrated Vulnerability Assessment of Transport Networks in the SCA

To analyse the integrated vulnerability of transport networks, total social travel cost (TSTC) was adopted, considering transfer modes from the SMRS to road networks. TSTC comprised six factors: TSTC from travel time costs, TSTC from operating costs of road networks, TSTC from operating costs of the SMRS, TSTC from road traffic accident costs, TSTC from environmental impact costs, and TSTC from car parking costs. After summing all six factors, both in normal and abnormal situations, the difference of the two TSTCs was defined as the integrated vulnerability of transport networks in the SCA. The vulnerability analysis was implemented on each of the six transport axes: 1st Incheon axis, 2nd Suwon axis, 3rd Seongnam axis, 4th Namyangju axis, 5th Uijeongbu axis, and 6th Goyang axis.

The 1st Incheon axis experiences the greatest increase of TSTC of the six transport axes. TSTC of the normal situation was equivalent to 353.29 billion KRW for one day. A disrupted 1st Incheon axis increases the TSTC to 366.61 billion KRW. The total vehicle-links is 698,837,500 on a normal day. This increases to 725,224,488 during a disruption on the 1st Incheon axis, or 3.8%. Conversely, the total passenger segments on the SMRS decreases from 90,278,605 to 82,408,469, or –8.7%.

A disruption on the 2nd Suwon axis causes the second largest increase of TSTC at 12.12 billion KRW/day, a 3.4% increase, from 353.29 to 365.41 billion KRW/day. This value increases to 84.83 billion KRW if the disruption lasts a week. However, if the TSTC is divided by Suwon axis' population, it changes from second position to last position when the TSTC is measured per capita. In other words, the 2nd Suwon axis is the most stable one from the perspective of average vulnerability. The whole road network experiences an increase of 14.03 billion KRW/day, or 4.5%. However, the SMRS reveals a decrease of 4.6% or 1.91 billion KRW/day.

The total vehicle-links is 698,837,500 on a normal day. On the 2nd Suwon axis's disruption, this changes to 723,237,119, an increase of 3.5%. Conversely, the total passenger segments on the SMRS decreases from 90,278,605 to 83,778,790. Other Bus increases by a massive 45.9%, from 3,508,863 to 5,120,400 vehicles when the section from Oido Station to Sadang Station is not available.

Disruption of the 3rd Seongnam axis increases total TSTC to 7.19 billion KRW/day, or 2.0%, from 353.29 to 360.48 billion KRW/day. This changes to 50.34 billion KRW where the disruption extends to one week. This axis is the fifth lowest change of TSTC per capita, although the change in the gross TSTC is third. All road networks increase by 8.68 billion KRW/day, or 2.8%. However, SMRS decreases by 3.6% or 1.49 billion KRW/day.

When there is a disruptive event on the 3rd Seongnam axis, the total vehicle-links is 710,154,113 during disruption, compared with 698,837,500 vehicles normally. All passenger segments on the SMRS decrease from 90,278,605 to 85,734,743 in the disruptive situation. Other Bus showed the highest increase among road transport modes at 22.0%, from 3,508,863 to 4,279,530 vehicles. But the increase of Other Bus is smaller than that of 1st Incheon or 2nd Suwon axes. Car, taxi, and truck all show very little change in a disruptive event, at 1.6%, 5.2%, and –0.1% respectively.

Disruption of 4th Namyangju axis causes an increase of total TSTC to 5.77 billion KRW/day, or 1.6% increase, from 353.29 to 359.06 billion KRW/day. This value grows to 40.37 billion KRW/day where the disruption extends to one week. The road networks increase by 6.28 billion KRW/day, or 2.0%. The SMRS decreases by 1.2%, from 41.12 to 40.61 billion KRW/day, the smallest drop of the six axes. Total TSTC from the travel time in road networks increases 2.8%, from 144.80 to 148.91 billion KRW. With a disruption on the 4th Namyangju axis, the number of vehicles on all links increases by 0.7%, from 698,837,500 to 703,603504. On the other hand, passenger segments on the SMRS decrease by 1.6%, from 90,278,605 to 88,871,078, during disruption.

Scenario 5 for the Uijeongbu axis increases TSTC to 5.11 billion KRW/day, or 1.4%, from 353.29 to 358.40. This value was the lowest gross increase of TSTC among the six axes. However, after dividing by its population, the increase of TSTC per person is 5,753.85 KRW/man-day, which means it is the most vulnerable axis. The increase would become 35.78 billion KRW if the disruption continued for one week. All road traffic increases by 5.59 billion KRW/day, or 1.8%. TSTC from travel time increases 2.6%, from 144.80 to 148.56 billion KRW. TSTC from road traffic accidents remained almost the same in spite of the disruption. Subtotal of road networks TSTC increases 1.8%, from 312.17 to 317.76 billion KRW.

The Scenario 5 disruptive event in the SMRS Line 1 with 5th Uijeongbu transport axis causes a 0.4% increase of car use from 501,629,118 to 503,657,221 vehicle-links. Even Other Bus increases just 6.9%, from 3,508,863 to 3,751,588 vehicles. These increasing rates are quite small when compared to the other transport axes. This trend was similar to the decrease of passengers on the SMRS.

Disruptions on the 6th Goyang axis increases total TSTC to 6.38 billion KRW/day, or 1.8%, from 353.29 to 359.67 billion KRW/day. From the gross increase of TSTC, this axis ranked fourth, and third from the increase of TSTC per capita. TSTC from travel time road networks increases 2.3%, from 312.17 to 319.46 billion KRW/day.

When there is a disruptive event on the 6th Goyang axis, the total vehicles-links is 705,947,895 during disruption, compared to 698,837,500 normally. This is a 1.0% increase. All the passenger segments on the SMRS decreases from 90,278,605 to 87,392,969 in the disruptive situation, or –3.2%. These relatively small changes are directly related to the small change of TSTC, similar to the 4th Namyangju transport axis from the viewpoint of gross increase as well as increase per capita.

9.1.2 Travellers' Choices during Disruptive Events on the SMRS

The online survey had 1,415 respondents, without separating the six transport axes. 385 participants, or 27.2%, chose car as their alternative transport mode. 11.1% preferred to use a taxi in an emergency situation. Bus was the favourite transport mode for travellers when they could not use the SMRS; 457 participants, or 32.3%, would take a bus as a substitute of the partially suspended SMRS. Other available SMRS lines were selected as the second dominant transport mode, by 402 participants, or 28.4%. Those who decided to work at home or bike/walk comprised 0.6% and 0.4% respectively. In other words, the effect of working at home could be not taken into account when alternative mode shares were analysed.

The most popular source for information on disruptions was the Internet, with scores from 32.2% to 36.5%. The probable reason is the high usage of smart phones, possessed by 83.2% of all South Koreans in 2015. Mass Media ranked second, with 28.3% on average. Surprisingly, Social Networks and Notice from Company were not much preferred to other sources. In contrast, about one fifth of travellers expected the Government to notify them of disruptive events.

In a real situation, people are more dependent on the Internet and Mass Media than in the theoretical situation. Notice from both Company and Government were much lower than stated desires. Although 19.7% of travellers wanted Notice from Government, only 8.6% had experienced this. The gap between travellers' expectations and delivery from each source should be considered when devising strategies for more resilient transport networks.

On average, 32.7% of all respondents had experienced disruption, while 67.3% had not. These ratios did not vary much by transport axis except in one case. Only 25.9% of travellers on the 3rd Seongnam axis had experienced a disruptive event. For long-term disruption, 245 participants stated that they would change to alternative modes within three days; 115 participants chose a period of between four days and seven days; while 135 participants would move to a different transport mode when disruptive events continued for longer.

On the relationship between age and alternative mode shares, the generation in their 20s and 30s demonstrated high dependency on public transport with car choice considerably lower. Other SMRS lines were selected by 39.3% of those in their 20s, but car was chosen by 10.5%. In contrast, 21.6% of the 40s age group determined to use other SMRS lines, while 38.2% preferred car as their major alternative mode. This suggests that the younger generation has difficulty affording cars as their main transport mode in both an abnormal and normal situation. Conversely, older age groups are more affluent when it comes to using private cars as their commuting tool.

From the viewpoint of monthly income, households with lower incomes are less able to use a car as their alternative mode. Although the average for car was 27.3%, in households with a monthly income less than 2 million KRW, only 8% of respondents chose car. Conversely, the ratios of bus or Other SMRS for the low-income households were considerably higher than the high-income ones. 22.5% of those with income between 2-3 million KRW stated that they would like to use car for commuting in an emergency situation. However, for an income more than 3 million KRW, there were no significant differences among income groups on choice of alternative transport modes. Arrival times between midnight and 9 am suggest that travellers in the early morning had a greater possibility of using a car during a disruption. The ratio of car as alternative mode decreased from 33.3% before 7 am to 24.2% before 9 am. However, commuters who are able to arrive at their workplace after 9 am showed less preference for car and high dependency on public transport like bus and Other SMRS lines.

9.1.3 Management Strategies for More Reliable Services of the Transport Networks

One of the important issues for the disrupted SMRS is the sudden decrease of transport supply and unsatisfied travel demand in the local area. The gap between these two may be a lack of information about the disruptive event. Internet services provided through mobile phones can be the most efficient tool for disseminating information. Another useful method is a mobile application that delivers transport information, such as the operation schedules of all SMRS lines, and transfer information within the SMRS or onto different transport modes. In addition, CBS can be useful to disseminate information about a disruption, similar to the sending of a disaster message through CBS. It is possible for the government to simultaneously propagate messages through CBS to all mobile phone users within a selected area.

The SMRS has 11 operators in charge of 18 separate lines, within the SCA. When there is a disruption on a specific section, other operators may fail to respond to the situation as they only have an indirect responsibility. Furthermore, there may be barriers to cooperation between different operators for obtaining the right equipment to resolve a disruption. A single operator in charge of the whole of the SMRS might be an ideal organisation to solve a non-standard situation, and could minimise the impact of that disruption.

While the disrupted railway section is being recovered, it is desirable for passengers to have alternatives to continue their original trips or adjust their routes or initial modes. However, it is impossible to predict where an event will occur. If railway network operators also controlled other public transit modes such as buses, they would have the potential to provide passengers with detouring modes around a disabled section. They could then directly respond to disruptions on the SMRS. However, of the 11 SMRS operators, only Incheon Transit Corporation operates road transit as well as Incheon Metro Lines 1 and 2. The remaining operators need to be supported with other public transit modes like bus.

A train that is unable to move by its own power can be a substantial obstacle to the entire operation. Passing track and refuge tracks can be an effective solution to this problem. Passing track can minimise the impact of the faulty train by letting other trains detour past the disrupted section. Passing track or refuge track should be included whenever a new railway line is constructed in order to minimise the impact of a disruption to part of the SMRS. Moreover, passing track or refuge track should be added to current lines where possible, depending on the probability of disruption to each section of the SMRS.

Emergency response manuals focus on the operators' actions in the event of disruption to their lines. The manuals have to be prepared by types of disruption and by location of disruption. Neither the MOLIT standard nor the operator's manual covers the location of a disaster. Each line of the SMRS covers a wide area, and the action plan may differ depending on the location of the disruption. Resources available can vary with distance from major stations, train bases, refuge track, and recovery material storage. Therefore, after determining current storage of recovery material, the information should be shared with and utilised by different SMRS operators. Although normal operation of each line of the SMRS is divided into different organisations, emergency response should be executed by a cooperative of the different SMRS operators.

Drivers of trains and station employees are responsible for the emergency when a disruptive event occurs. However, it is very difficult for train drivers or station employees to control circumstances because there will be many confused passengers who want to escape from the situation as soon as possible. Passengers should have been previously instructed on how to react properly to a serious disruption. Current safety education has usually focused on what train drivers have to do and how station staff should respond in an emergency situation, rather than the main guidance for passengers in unusual events. It is essential for passengers to distinguish what they should do, what they can do, and what they should not do, during an emergency.

The criteria for preliminary feasibility studies have been: economic feasibility, environmental impact, and balanced regional development. Although road traffic accident reduction is mentioned in the process of economic feasibility analysis, ancillary design items have a tendency to be excluded because they increase the total project costs. Even a newly planned railway project is likely to omit refuge tracks to minimise total project costs and enhance economic feasibility. In the current criteria for feasibility studies to assess new infrastructure projects, the safety category must be added. Safety criteria during the feasibility assessment are strongly linked to a separate budget system for safety administration. A fundamental paradigm shift for safety is the Safety Special Account in the government budget, so that safety-related administration can be addressed independently of economic benefit-cost ratios. Therefore, a safety tax may be a crucial element for the separate safety budget account, which produces different criteria to make a safer environment.

Three metropolitan cities are located within the SCA, where more than 25 million people live. The total length of the SMRS is 1014.4 km, and has 636 stations. More than 10 million commuters travel daily in the SCA. These facts suggest a new integrated administrative organisation to solve transport problems efficiently. A special Government Act needs to be passed to grant the new transport authority legal status. Independent personnel rights and self-governing revenue and budget planning are essential factors so that the new transport authority is involved with transport issues around the SCA, including response to emergencies on the SMRS.

The introduction of a safety tax would be a good impetus for people to realise that safety is not free and for government to concentrate on safety policy. Also important is that people have to understand their own responsibility, as well as the role of government, during unexpected disasters. Following safety guidelines should be taken for granted, although it might be uncomfortable. The more invested in safety, the safer circumstances become.

9.2 Contributions

The contributions through this work may be enumerated as four: a combination of different transport networks with the concept of total social travel costs; application of personal responses to determine trip choice in the disrupted situation; analysis of the weakest transport axis around the Seoul Capital Area and suggestion for preparation; and management strategies to reduce the vulnerability of transport networks in the SCA. These 4 points are unique contributions that the wider literature has not identified when it comes to vulnerability assessment of transport networks.

First, compared with previous research, an integrated vulnerability assessment between different transport modes was identified for the first time among various vulnerability analyses in the transport networks. It was found that travellers, especially commuters, would like to continue their original trips when there was an unexpected situation. Therefore, analysis was undertaken of the exact impact of an incident on the subway networks, the derived influence on the adjacent road networks, and the pure impact of the incident on the SMRS.

Next, this work assessed the vulnerability of public transport networks from individual users' aspects, which was also a newly-tried approach compared with existing literature that covered only physical or topological characteristics. It was found that travellers, especially commuters, wanted to continue their initial trips, but travellers' mode choices in the disruptive environment might differ from those in the normal situation. Furthermore, the length that disruptive events continued impacts the mode choice of commuters, and this was also analysed.

Then, the vulnerability of public transport networks was assessed according to each transport axis in the Seoul Capital Area and the order of vulnerability was presented. This data will be useful for local and central government to prepare for the urgent situation such as flooding, fire, intentional attacks, and so on. Integrated vulnerability assessment could be added as an additional standard to evaluate infrastructure projects at the stage of preliminary feasibility study.

Finally, management strategies were suggested by interviews with 19 experts to intensify resilience of the transport networks in the SCA and to recommend a guideline for users during the disruption. Management strategies were classified into: how to solve disruptive events on the SMRS efficiently; how to minimise the impact of disruptions on the SMRS; and long-term strategies to strengthen transport networks in the SCA. Governments and operators of the SMRS could practice trial-runs of supposed disruptions and strengthen its weak points to reduce the impact of malfunctions. Travellers, especially commuters, could cope with a real situation easily with guidelines that minimise trial and error at peak times.

9.3 Limitations and Suggestions for Future Study

Although this work has produced several contributions, it also has some limitations due to the assumptions used. This section covers the limitation of the work and suggestions for future research.

First, the integrated vulnerability of transport networks was assessed through the online survey, which was composed of commuters' responses, not reflecting all types of trip purposes. This study assumed that commuters' choices in the disrupted operation of the SMRS were the same with non-commuters' choices in the same situation. Commuters are probably more inelastic when it comes to giving up their original travel in the abnormal situation of the SMRS (Storchmann, 2001). In other words, this assumption might produce an expanded total social travel costs (TSTC) within the SCA. Therefore, if the vulnerability assessment of transport networks was based on a survey including all types of trip purposes, the result could suggest a more realistic scale of TSTC.

Secondly, the online survey was originally planned to collect more than 400 participants for each transport axis, but ended up with 200 respondents or so on each. The maximum was 326 participants on the 2nd Suwon axis, while the 4th Namyangju axis recorded the minimum of 200 respondents. Consequently, during the analysis, the acceptable margin of error was changed from 5% to 7%, which meant that the precision of alternative mode choices became less reliable compared to the initial goal. It is recommended that future study would be grounded on more samples from each transport axis.

Thirdly, this work assumed that all travellers had been perfectly informed of the information of a disruptive event on the SMRS before they chose their alternative transport modes. But, in real life, it is impossible for information about disruptions to be delivered to all travellers. A number of travellers may recognise that a section of the SMRS is not available only when they arrive at the suspended stations, and then cannot choose car as their alternative mode and have to spend more time to determine their alternatives. Accordingly, future study must simulate more realistically the dissemination of information about the disrupted SMRS.

Fourthly, it was assumed that chartered buses could be provided without delay, regardless of the location of the disruptive event. This assumption was also quite far from reality. It probably takes a few hours for chartered buses to be made available for use as emergency transport modes, causing additional TSTC. Future study needs to analyse the location of chartered buses in line with the timelines of the day, so that a scenario for a disruptive event would produce a more persuasive result comparable to a real situation. Similarly, further research needs to be based on the capacity constraints related to taxis and car parking spaces.

Finally, TransCAD is macro simulation software which can analyse total travel cost of each link by transport mode. The method used here was an aggregate approach. If 27% of the SMRS demand wants to transfer to road networks by driving their cars, all of 27% of the SMRS demand were assigned simultaneously to road networks in line with each origin/destination. It is possible to calculate the scale of integrated vulnerability of transport networks by just comparing the normal situation and the disrupted situation. However, in a real situation, one traveller's modal choice during the disruptive event has an impact on other travellers' modal choices. In other words, the increased TSTC needs to be analysed with a disaggregate approach. If future study can identify the traffic demand function in a disruptive situation, the disaggregate approach could produce a more exact result for vulnerability assessment.

APPENDICES

Appendix 1. Online Survey Questionnaire

Commute Travel Survey with Disruptive Events of Subway/Train in the Seoul Capital Area

About this questionnaire

This questionnaire is to help the researcher to find out how you commute and your choice in the case of disruptive events on the Seoul Metropolitan Railway Systems. It will take about 10-20 minutes to complete.

How to complete the questionnaire

Not all questions are compulsory. However, to make our study a success, we need you to answer as many questions as you can. Remember, there are no right or wrong answers.

Some questions ask you to **select a box**. Pleas tick the box that applies to you.

Example Are you male or female? Tick one only ☑ Male ☐ Female

Other questions ask you to **type numbers or letters** in a box.

Example What is the distance from home to work? [13] km

Don't worry if you make a mistake – you will be able to change your response by simply selecting the appropriate new response, or re-typing your answer in a box. You will also be able to go back to any page to change a response – this can be done by clicking on the "PREVIOUS" button located at the bottom right hand side of the page.

If you have any questions or concern about completing this survey please email wo1n13@soton.ac.uk **or call 070 4898 6152 or +44 75 7885 3053**

Before you begin

1. Are you 18 or over 18?

- ☐ **Yes** ☞ **Go to next Question**
- ☐ **No** ☞ **Thank you for your interest but you cannot take part in this survey.**

2. Do you usually take a subway or a train as the main commuting mode?

- ☐ **Yes** ☞ **Go to next Question**
- ☐ **No** ☞ **Thank you for your interest but you cannot take part in this survey.**

3. Are you a commuter who works in Seoul and lives in Incheon or Gyeonggi Province?

- ☐ **Yes** ☞ **Go to next Question**
- ☐ **No** ☞ **Thank you for your interest but you cannot take part in this survey.**

*** Please tick(√) or write down to all questions**

Section A

<About your commuting travel in normal situation>

1. Where is your home? *example:* [Incheon City] [Yeonsu-Gu] [Dongchun1-Dong]

Megacity /Province <Si/Do>	City/District/Region<Si/Gun/Gu>	Township<Dong/Myeon>

2. Where is your workplace? *example:* [Seoul City] [Seocho-Gu] [Bangbae1-Dong]

Megacity /Province <Si/Do>	City/District/Region<Si/Gun/Gu>	Township<Dong/Myeon>

3. What is the distance from home to work? [ ] km

(Please write it based on the routes you use most frequently as usual. *example* : 15 km)

4. What is the total travel time on average? (e.g. [01] hrs [10] mins) [ ] hrs [ ] mins

4-1. When is the usual departure time from home? (e.g. [07: 40 am]) [ ]

4-2. When is the usual arrival time to your workplace? (e.g. [08: 40 am]) [ ]

5. What modes do you use for commuting, in addition to walking?

☐ subway or train (including transfer)
☐ car and subway or train
☐ taxi and subway or train
☐ bus (including transfer) and subway or train
☐ other (please specify) [ ]

6. What is your main travel route during you are boarding on a subway or train?

6-1. What is your departure station? (e.g. [Line1 Dongam]) [ ]

6-2. What is your arrival station? (e.g. [Line2 Sadang]) [ ]

6-3. What is your transfer station? (e.g. [Line1,2 Shindorim]) [ ]

Section B

<About your commuting in a disruptive situation of subway or train line>

Part.1 **(Assumption) Assume the subway or train line that you use for the major part of your journey and brings you from your home town to the boundary of Seoul is not available from 05:00 am to 11:59 pm because of a disruptive event on the line.**

1. What will be your alternative commuting transport mode?

☐ car
☐ taxi
☐ bus
☐ car and bus
☐ taxi and bus
☐ car and train or subway (other lines)
☐ taxi and train or subway (other lines)
☐ bus and train or subway (other lines)
☐ taxi, bus and train or subway (other lines)
☐ not travel (working at home)
☐ other (please specify) [ ]

2. How long will it take to commute by an alternative commuting transport mode according to your estimation?

( ) minutes more than ordinary commuting time

3. How do you prefer to get information of disrupted subway operations? Please choose 2 of your preferences.

☐ SNS (Social Network Service)
☐ the Internet
☐ Mass Media (TV, Radio, Newspapers, etc.)
☐ Announcement from your company (Telephone, ARS, text message, etc.)
☐ Announcement from local or central government (Telephone, ARS, text message, etc.)
☐ other (please specify) [ ]

4. Have you ever experienced a one day disruption during you commute to work?

☐ **No** ☞ Go to Questions **Part.2 at the next page**
☐ **Yes** ☞ Go to Questions **4.1~4.3**

4.1 Which mode did you use for commuting to work?

☐ car
☐ taxi
☐ bus
☐ car and bus
☐ taxi and bus
☐ car and train or subway (other lines)
☐ taxi and train or subway (other lines)
☐ bus and train or subway (other lines)
☐ taxi, bus and train or subway (other lines)
☐ not travel (working at home)
☐ other (please specify) [ ]

4.2 How long did it take to commute by an alternative commuting transport mode when compared to a normal situation?

( ) minutes more than ordinary commuting time

4.3 How did you get information about the disrupted subway operation?

☐ SNS (Social Network Service)
☐ the Internet
☐ Mass Media (TV, Radio, Newspapers, etc.)
☐ Announcement from your company (Telephone, ARS, text message, etc.)
☐ Announcement from local or central government (Telephone, ARS, text message, etc.)
☐ other (please specify) [ ]

<u>Part.2</u> (Assumption) Assume the subway or train line that you use for the major part of your journey and brings you from your home town to the boundary of Seoul is not available for more than two days from the perspective of commuting to work and returning home because of a disruptive event on the line.

1. Are you going to change your alternative commuting transport mode compared with your choice of one-day disruption of subway or train?

☐ **No** ☞ Go to Questions **Section .C**
☐ **Yes** ☞ Go to Questions **2~4**

2. When are you going to change your alternative commuting transport mode?

Ans) More than ( ) days of operation stoppage due to a disruptive event on the subway or train line

3. What is your changed alternative commuting transport mode compared with your choice of one-day disruption of subway or train?

☐ car
☐ taxi
☐ bus
☐ car and bus
☐ taxi and bus
☐ car and train or subway (other lines)
☐ taxi and train or subway (other lines)
☐ bus and train or subway (other lines)
☐ taxi, bus, and train or subway (other lines)
☐ not travel (working at home)
☐ other (please specify) [ ]

4. What is the main reason for your changed alternative commuting transport mode in a long operation stoppage of the subway or train?

☐ total commuting travel time
☐ total commuting travel cost
☐ predictability of total commuting travel time
☐ comfort during commuting travel
☐ other (please specify) [ ]

Section C

<About you and your household>

1. Are you male or female? ☐ Male ☐ Female

2. How old are you? ☐ 18-29 ☐ 30-39 ☐ 40-49 ☐ 50-59 ☐ 60 or above

3. What is your total household income from all sources before tax per month?
(£1 = 1,800 KRW)

☐ up to 2,000,000 won (about £1,111)
☐ 2,000,001 won – 3,000,000 won (about £1,112 - £1,667)
☐ 3,000,001 won – 4,000,000 won (about £1,668 - £2,222)
☐ 4,000,001 won – 5,000,000 won (about £2,223 - £2,778)
☐ 5,000,001 won – 6,000,000 won (about £2,779 - £3,333)
☐ 6,000,001 won – 7,000,000 won (about £3,334 - £3,889)
☐ more than 7,000,001 won (over about £ 3890)

4. What is your highest educational qualification?

☐ primary school or no education ☐ middle school ☐ high school
☐ college ☐ university ☐ postgraduate school

5. What is your occupational sector?
☐ governmental sector ☐ professional sector ☐ administrative or clerical sector
☐ technical sector ☐ sales sector ☐ service sector
☐ production, drive or labour sector ☐ other

6. What is your main commuting period from home to work
(the criterion is arrival time to office)?

☐ from midnight to just before 7 a.m. ☐ from 7 a.m. to just before 8 a.m.
☐ from 8 a.m. to just before 9 a.m. ☐ from 9 a.m. to just before 10 a.m.
☐ from 10 a.m. to just before 11 a.m. ☐ from 11 a.m. to just before 12 a.m.
☐ from 12 a.m. to just before 5 p.m. ☐ from 5 p.m. to just before 9 p.m.
☐ from 9 p.m. to just before midnight

7. Do you have difficulties of using public transport, for example, due to physical disabilities?

☐ yes ☐ no

8. Can you work at home in case of disruption?

☐ **yes** ☐ **no**

9. How many people are in your household, including yourself?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

10. How many workers are in your household?

☐ 1 ☐ 2 ☐ 3 or more

11. How many cars do you have in your household?

☐ 0 ☐ 1 ☐ 2 ☐ 3 or more

12. What is the main use of the car you use most often?

☐ commute to/from work ☐ commute to/ from school ☐ business
☐ shopping or house usage ☐ leisure (sport, tour) ☐ other

Congratulations!

You've Completed the Questionnaire.

Thank You Very Much!

Appendix 2. Online Survey Results in the Six Transport Axes

Table A2-1. Alternative Mode Shares in 1st Incheon Axis

Alternative Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Auto	71	27.8%	Auto	82	32.2%
Taxi	14	5.5%	Taxi	31	12.2%
Bus	65	25.5%	Bus	65	25.5%
Auto+Bus	11	4.3%	O.SMRS	72	28.2%
Taxi+Bus	17	6.7%	W.Home	3	1.2%
Auto+Other Line of SMRS	5	2.0%	Etc.	2	0.8%
Taxi+Other Line of SMRS	8	3.1%	Sum	255	100.0%
Bus+Other Line of SMRS	51	20.0%			
Taxi+Bus+Other Line of SMRS	8	3.1%			
Working at Home	3	1.2%			
Etc.	2	0.8%			
Sum	255	100.0%			

Table A2-2. Alternative Mode Shares in 2nd Suwon Axis

Alternative Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Auto	70	21.5%	Auto	83	25.5%
Taxi	14	4.3%	Taxi	39	12.0%
Bus	109	33.4%	Bus	109	33.4%
Auto+Bus	13	4.0%	O.SMRS	92	28.2%
Taxi+Bus	25	7.7%	W.Home	1	0.3%
Auto+Other Line of SMRS	9	2.8%	Etc.	2	0.6%
Taxi+Other Line of SMRS	7	2.1%	Sum	326	100.0%
Bus+Other Line of SMRS	69	21.2%			
Taxi+Bus+Other Line of SMRS	7	2.1%			
Working at Home	1	0.3%			
Etc.	2	0.6%			
Sum	326	100.0%			

Figure A2-1. Alternative Mode Shares in 1st Incheon (left) and 2nd Suwon (right) Axis

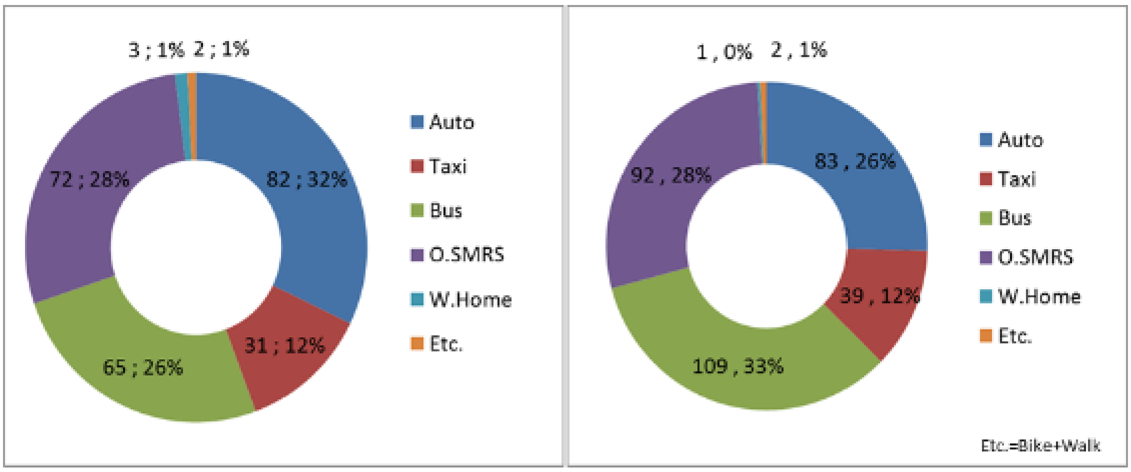


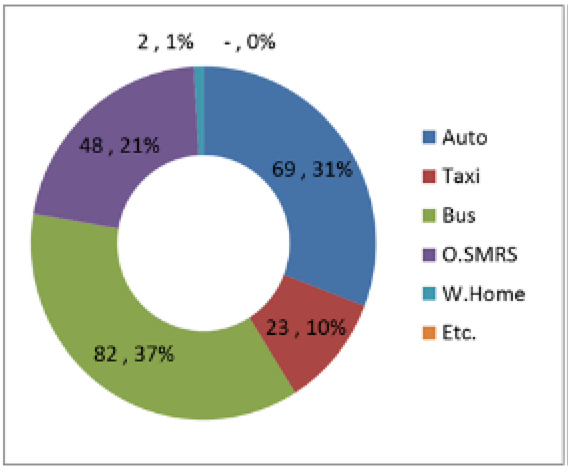
Table A2-3. Alternative Mode Shares in 3rd Seongnam Axis

Alternative Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Auto	57	25.4%	Auto	69	30.8%
Taxi	10	4.5%	Taxi	23	10.3%
Bus	82	36.6%	Bus	82	36.6%
Auto+Bus	12	5.4%	O.SMRS	48	21.4%
Taxi+Bus	13	5.8%	W.Home	2	0.9%
Auto+Other Line of SMRS	3	1.3%	Etc.	-	0.0%
Taxi+Other Line of SMRS	5	2.2%	Sum	224	100.0%
Bus+Other Line of SMRS	38	17.0%			
Taxi+Bus+Other Line of SMRS	2	0.9%			
Working at Home	2	0.9%			
Etc.	-	0.0%			
Sum	224	100.0%			

Table A2-4. Alternative Mode Shares in 4th Namyangju Axis

Alternative Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Auto	41	20.5%	Auto	47	23.5%
Taxi	10	5.0%	Taxi	31	15.5%
Bus	61	30.5%	Bus	61	30.5%
Auto+Bus	6	3.0%	O.SMRS	59	29.5%
Taxi+Bus	21	10.5%	W.Home	1	0.5%
Auto+Other Line of SMRS	8	4.0%	Etc.	1	0.5%
Taxi+Other Line of SMRS	2	1.0%	Sum	200	100.0%
Bus+Other Line of SMRS	43	21.5%			
Taxi+Bus+Other Line of SMRS	6	3.0%			
Working at Home	1	0.5%			
Etc.	1	0.5%			
Sum	200	100.0%			

Figure A2-2. Alternative Mode Shares in 3rd Seongnam (left) and 4th Namyangju (right) Axis



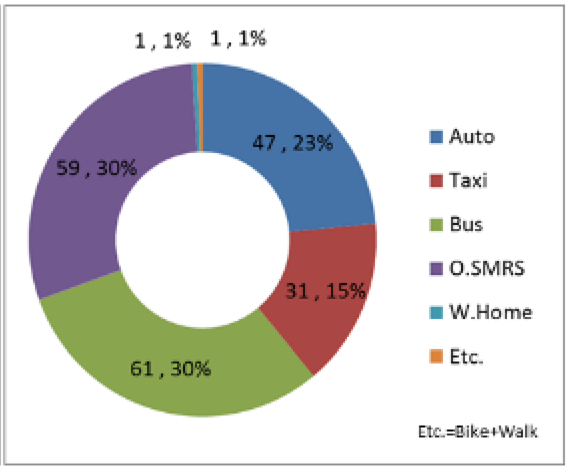


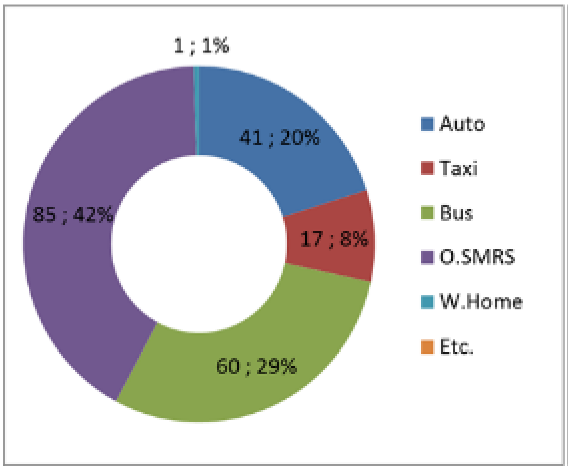
Table A2-5. Alternative Mode Shares in 5th Uijeongbu Axis

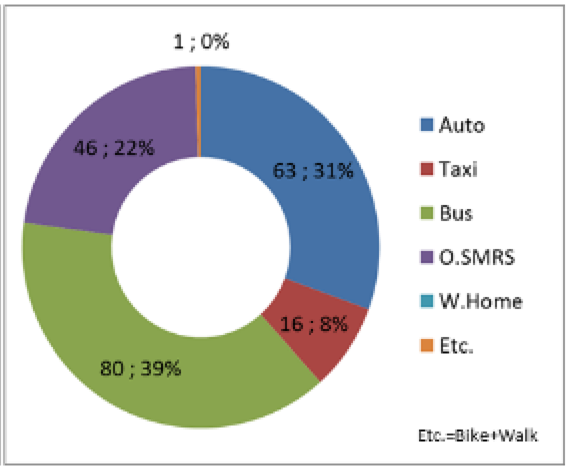
Alternative Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Auto	38	18.6%	Auto	41	20.1%
Taxi	4	2.0%	Taxi	17	8.3%
Bus	60	29.4%	Bus	60	29.4%
Auto+Bus	3	1.5%	O.SMRS	85	41.7%
Taxi+Bus	13	6.4%	W.Home	1	0.5%
Auto+Other Line of SMRS	10	4.9%	Etc.	-	0.0%
Taxi+Other Line of SMRS	6	2.9%	Sum	204	100.0%
Bus+Other Line of SMRS	67	32.8%			
Taxi+Bus+Other Line of SMRS	2	1.0%			
Working at Home	1	0.5%			
Etc.	-	0.0%			
Sum	204	100.0%			

Table A2-6. Alternative Mode Shares in 6th Goyang Axis

Alternative Mode	Responses	Ratio	Alter. Mode	Responses	Ratio
Auto	54	26.2%	Auto	63	30.6%
Taxi	7	3.4%	Taxi	16	7.8%
Bus	80	38.8%	Bus	80	38.8%
Auto+Bus	9	4.4%	O.SMRS	46	22.3%
Taxi+Bus	9	4.4%	W.Home	-	0.0%
Auto+Other Line of SMRS	2	1.0%	Etc.	1	0.5%
Taxi+Other Line of SMRS	3	1.5%	Sum	206	100.0%
Bus+Other Line of SMRS	39	18.9%			
Taxi+Bus+Other Line of SMRS	2	1.0%			
Working at Home	-	0.0%			
Etc.	1	0.5%			
Sum	206	100.0%			

Figure A2-3. Alternative Mode Shares in 5th Uijeongbu (left) and 6th Goyang (right) Axis





Appendix 3. Questionnaire for Experts Interview

Management Strategy of the Transport Networks In the Seoul Capital Area, Korea

Background

This questionnaire is to help the researcher to find how transport networks can be more resilient when there is a disruptive event on the Seoul Metropolitan Railway Systems (SMRS). To minimize the travel time and costs of travellers in the Seoul Capital Area (SCA), opinions of experts group from operators of SMRS, research institutes, local government and central government will be collected. Through this expert consultation, maintenance and operation strategies will be suggested, targeting for the disrupted SMRS and affected road networks in the SCA.

Interview Questionnaire

Section A: Personal Information

Please complete your personal information firstly!

1. Organization: (   )

2. Level of Current Position: Choose one in the followed category

- Staff of working level (   )

- Manager of middle level (   )

- Director of high level (   )

3. Title of current department: (   )

4. Length of total career: (   ) years

Section B: Current Information of Disruptive Events on SMRS

1. Does your organization have any data on disruptive events on SMRS or the lines that your organization is responsible for?

2. How can the causes of the disruptive events on SMRS be classified?

3. How long did the disruptive events continue when they happened?

4. Which solutions does your organization have in order to react to a disruptive event on SMRS?

Section C: Current Responses to the Disruptive Events on SMRS

1. What does your organization do in order to provide passengers with alternatives when a section of SMRS becomes out of service suddenly?

2. How does your organization communicate with people in order to disseminate the information of the suspended section of SMRS?

3. How does your organization co-work with related organizations to resolve the disruptive event on SMRS?

4. Are there any difficulties for you or your organization to measure the disruptive events on SMRS?

Section D: Suggestions for more efficient ways to resolve the disruptive Events on SMRS

1. Can you classify your ideas to resolve the disruptive events on SMRS more efficiently according to the amount of costs and span of time within your organization?

Time / **Costs**	**Short-Term** (≤1 Year)	**Long-Term** (> 1 Year)
Not Much (≤0.5 bill. KRW)	- - - -	- - - -

Much (>0.5 bill. KRW)	- - - -	- - - -

* 1 million GBP ≒ 1.4 billion KRW

2. Do you have any suggestion for the related organizations in terms of what you want them to do to resolve the disruptive events on SMRS more efficiently?

3. Do you have any idea that has not been mentioned in the above questions regarding the vulnerability of transport networks in SCA?

Appendix 4. Additional Tables

Table A4-1. Autonomous Cities in Seoul Metropolitan City (2015)

Autonomous Cities	Population	Ratio	Area(km^2)	Ratio
Seoul Metropolitan City	9,904,312	100.0%	605.25	100.0%
Jongno-Gu	161,521	1.6%	23.91	4.0%
Jung-Gu	128,478	1.3%	9.96	1.6%
Yongsan-Gu	227,282	2.3%	21.87	3.6%
Seongdong-Gu	295,006	3.0%	16.86	2.8%
Gwangjin-Gu	368,199	3.7%	17.06	2.8%
Dongdaemun-Gu	364,787	3.7%	14.21	2.3%
Jungrang-Gu	403,237	4.1%	18.50	3.1%
Seongbuk-Gu	456,844	4.6%	24.58	4.1%
Gangbuk-Gu	319,992	3.2%	23.60	3.9%
Dobong-Gu	340,095	3.4%	20.71	3.4%
Nowon-Gu	562,996	5.7%	35.44	5.9%
Eunpyeong-Gu	478,374	4.8%	29.70	4.9%
Seodaemun-Gu	308,768	3.1%	17.61	2.9%
Mapo-Gu	381,330	3.9%	23.84	3.9%
Yangcheon-Gu	465,512	4.7%	17.40	2.9%
Gangseo-Gu	570,507	5.8%	41.44	6.8%
Guro-Gu	444,832	4.5%	20.12	3.3%
Geumcheon-Gu	250,690	2.5%	13.02	2.2%
Yeongdeungpo-Gu	406,528	4.1%	24.53	4.1%
Dongjak-Gu	407,894	4.1%	16.35	2.7%
Gwanak-Gu	519,622	5.2%	29.57	4.9%
Seocho-Gu	420,804	4.2%	47.00	7.8%
Gangnam-Gu	541,688	5.5%	39.50	6.5%
Songpa-Gu	634,941	6.4%	33.88	5.6%
Gangdong-Gu	444,385	4.5%	24.59	4.1%

Source: Korean Statistical Information Service, http://kosis.kr (adapted, 2017)

Table A4-2. Autonomous Cities in Incheon Metropolitan City (2015)

Autonomous Cities	Population	Ratio	Area(km^2)	Ratio
Incheon Metropolitan City	2,890,451	100.0%	1,048.98	100.0%
Jung-Gu	112,910	3.9%	133.46	12.7%
Dong-Gu	71,054	2.5%	7.19	0.7%
Nam-Gu	405,746	14.0%	24.84	2.4%
Yeonsu-Gu	317,172	11.0%	50.07	4.8%
Namdong-Gu	527,324	18.2%	57.03	5.4%
Bupyeong-Gu	548,461	19.0%	32.00	3.1%
Gyeyang-Gu	327,311	11.3%	45.57	4.3%
Seo-Gu	499,540	17.3%	115.18	11.0%
Ganghwa-County	62,291	2.2%	411.43	39.2%
Ongjin-County	18,642	0.6%	172.19	16.4%

Source: Korean Statistical Information Service, http://kosis.kr (adapted, 2017)

Table A4-3. Autonomous Cities in Gyeonggi Province (2015)

Autonomous Cities	Population	Ratio	Area(km^2)	Ratio
Gyeonggi Province	12,479,061	100.0%	10,175.34	100.0%
Suwon-City	1,194,313	9.6%	121.05	1.2%
Seongnam-City	948,757	7.6%	141.66	1.4%
Uijeongbu-City	421,579	3.4%	81.54	0.8%
Anyang-City	585,177	4.7%	58.47	0.6%
Bucheon-City	843,794	6.8%	53.44	0.5%
Gwangmyeong-City	338,509	2.7%	38.52	0.4%
Pyeongtaek-City	457,873	3.7%	458.12	4.5%
Dongducheon-City	97,424	0.8%	95.67	0.9%
Ansan-City	747,035	6.0%	150.79	1.5%
Goyang-City	990,073	7.9%	268.08	2.6%
Gwacheon-City	64,817	0.5%	35.87	0.4%
Guri-City	180,063	1.4%	33.31	0.3%
Namyangju-City	629,061	5.0%	458.02	4.5%

Autonomous Cities	Population	Ratio	Area(km^2)	Ratio
Osan-City	213,840	1.7%	42.73	0.4%
Siheung-City	425,184	3.4%	135.79	1.3%
Gunpo-City	285,721	2.3%	36.41	0.4%
Uiwang-City	154,879	1.2%	53.99	0.5%
Hanam-City	154,838	1.2%	93.03	0.9%
Yongin-City	971,327	7.8%	591.32	5.8%
Paju-City	415,345	3.3%	672.89	6.6%
Icheon-City	209,003	1.7%	461.36	4.5%
Anseong-City	194,765	1.6%	553.41	5.4%
Gimpo-City	352,683	2.8%	276.59	2.7%
Hwaseong-City	608,725	4.9%	689.73	6.8%
Gwangju-City	310,278	2.5%	431.05	4.2%
Yangju-City	205,988	1.7%	310.28	3.0%
Pocheon-City	163,388	1.3%	826.52	8.1%
Yeoju-City	109,937	0.9%	608.32	6.0%
Yeoncheon-County	43,846	0.4%	676.01	6.6%
Gapyeong-County	58,909	0.5%	843.66	8.3%
Yangpyeong-County	101,930	0.8%	877.69	8.6%

Source: Korean Statistical Information Service, http://kosis.kr (adapted, 2017)

Table A4-4. Trips for Commuting to Work by Destination

(Unit: trip/day)

Desti-nation	2006		2007		2010		2011		2012		2013		Average Annual Increasing Rate
Seoul	4,510,850	49.8%	4,565,639	49.2%	5,284,771	49.9%	5,351,249	49.1%	5,488,315	49.5%	5,371,515	48.6%	2.5%
Incheon	902,164	10.0%	933,258	10.1%	1,039,065	9.8%	1,062,639	9.7%	1,052,093	9.5%	1,076,269	9.7%	2.6%
Gyeonggi	3,645,708	40.2%	3,774,922	40.7%	4,272,715	40.3%	4,487,092	41.2%	4,547,799	41.0%	4,615,280	41.7%	3.4%
Subtotal	9,058,722	100.0%	9,273,819	100.0%	10,596,551	100.0%	10,900,980	100.0%	11,088,207	100.0%	11,063,064	100.0%	2.9%

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area

Table A4-5. Trips by Car from Outside of Seoul to Seoul

(Unit: trip/day)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	293,182	313,554	300,743	308,290	301,101	307,874
Suwon	356,011	378,069	331,267	338,508	326,794	316,872
Seongnam	236,653	262,398	227,762	232,968	227,208	225,962
Namyangju	215,960	240,678	222,225	224,970	217,303	216,410
Uijeongbu	94,055	100,003	93,408	94,750	91,212	89,782
Goyang	180,907	222,446	185,922	191,805	188,192	186,318
Subtotal	1,376,768	1,517,148	1,361,327	1,391,291	1,351,810	1,343,218

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-6. Modal Sharing Ratio of Car for Trips from Outside of Seoul to Seoul

(Unit: %)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	38.92%	41.62%	40.61%	39.27%	36.67%	36.86%
Suwon	39.04%	40.79%	36.73%	36.15%	35.67%	34.03%
Seongnam	41.24%	45.32%	40.56%	39.83%	38.47%	36.98%
Namyangju	52.81%	50.49%	46.13%	44.46%	44.59%	42.76%
Uijeongbu	37.78%	41.82%	39.29%	38.32%	38.04%	36.66%
Goyang	47.85%	49.92%	44.67%	44.50%	43.39%	41.80%
SCA	42.04%	44.35%	40.76%	39.86%	38.75%	37.58%

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-7. Trips by Bus from Outside of Seoul to Seoul

(Unit: trip/day)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	110,326	118,477	134,044	140,891	143,924	154,160
Suwon	193,745	197,962	212,140	243,237	231,186	242,126
Seongnam	154,528	157,334	162,760	160,327	159,219	163,460
Namyangju	127,345	140,904	160,683	171,070	156,770	166,796
Uijeongbu	42,176	51,877	49,011	53,607	49,231	50,036
Goyang	82,380	115,158	109,039	119,357	114,544	115,606
Subtotal	710,500	781,712	827,677	888,489	854,874	892,184

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-8. Modal Sharing Ratio of Bus for Trips from Outside of Seoul to Seoul

(Unit: %)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	14.65%	15.73%	18.10%	17.94%	17.53%	18.45%
Suwon	21.25%	21.36%	23.52%	25.98%	25.24%	26.00%
Seongnam	26.93%	27.18%	28.98%	27.41%	26.96%	26.75%
Namyangju	31.14%	29.56%	33.35%	33.81%	32.17%	32.96%
Uijeongbu	16.94%	21.70%	20.62%	21.68%	20.53%	20.43%
Goyang	21.79%	25.84%	26.20%	27.69%	26.41%	25.93%
SCA	21.70%	22.85%	24.78%	25.45%	24.51%	24.96%

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-9. Trips by Subway from Outside of Seoul to Seoul

(Unit: trip/day)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	263,615	223,200	233,219	260,582	300,702	297,507
Suwon	248,836	247,181	260,673	257,602	264,781	278,939
Seongnam	107,435	120,042	124,308	144,162	156,937	174,362
Namyangju	9,860	19,497	33,701	43,327	40,099	46,253
Uijeongbu	70,552	60,663	73,384	76,768	77,185	82,455
Goyang	71,764	65,228	85,312	83,329	93,401	106,604
Subtotal	772,062	735,811	810,597	865,770	933,105	986,120

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-10. Modal Sharing Ratio of Subway for Trips from Outside of Seoul to Seoul

(Unit: %)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	35.00%	29.63%	31.49%	33.19%	36.62%	35.61%
Suwon	27.29%	26.67%	28.91%	27.51%	28.90%	29.96%
Seongnam	18.72%	20.74%	22.14%	24.65%	26.58%	28.54%
Namyangju	2.41%	4.09%	7.00%	8.56%	8.23%	9.14%
Uijeongbu	28.34%	25.37%	30.87%	31.04%	32.19%	33.67%
Goyang	18.98%	14.64%	20.50%	19.33%	21.54%	23.91%
SCA	23.58%	21.51%	24.27%	24.80%	26.75%	27.59%

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-11. Trips by Taxi from Outside of Seoul to Seoul

(Unit: trip/day)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	32,854	19,443	15,414	15,447	15,530	15,594
Suwon	42,252	40,782	35,343	35,039	34,973	35,019
Seongnam	18,577	11,567	14,518	14,952	14,976	15,504
Namyangju	11,848	20,228	15,883	15,755	15,771	16,581
Uijeongbu	10,677	4,144	3,569	3,557	3,572	3,597
Goyang	12,075	8,965	10,092	10,215	10,306	10,555
Subtotal	128,283	105,129	94,819	94,965	95,128	96,850

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-12. Modal Sharing Ratio of Taxi for Trips from Outside of Seoul to Seoul

(Unit: %)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	4.36%	2.58%	2.08%	1.97%	1.89%	1.87%
Suwon	4.63%	4.40%	3.92%	3.74%	3.82%	3.76%
Seongnam	3.24%	2.00%	2.59%	2.56%	2.54%	2.54%
Namyangju	2.90%	4.24%	3.30%	3.11%	3.24%	3.28%
Uijeongbu	4.29%	1.73%	1.50%	1.44%	1.49%	1.47%
Goyang	3.19%	2.01%	2.42%	2.37%	2.38%	2.37%
SCA	3.92%	3.07%	2.84%	2.72%	2.73%	2.71%

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-13. Trips by Other modes from Outside of Seoul to Seoul

(Unit: trip/day)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	53,243	78,700	57,184	59,929	59,869	60,220
Suwon	71,026	62,924	62,364	61,928	58,375	58,216
Seongnam	56,631	27,585	32,209	32,482	32,201	31,744
Namyangju	43,924	55,356	49,291	50,833	57,383	60,021
Uijeongbu	31,502	22,423	18,373	18,608	18,579	19,015
Goyang	30,941	33,794	25,886	26,355	27,246	26,681
Subtotal	287,267	280,782	245,307	250,135	253,653	255,897

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-14. Modal Sharing Ratio of Other Modes for Trips from Outside of Seoul to Seoul

(Unit: %)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	7.07%	10.45%	7.72%	7.63%	7.29%	7.21%
Suwon	7.79%	6.79%	6.92%	6.61%	6.37%	6.25%
Seongnam	9.87%	4.76%	5.74%	5.55%	5.45%	5.20%
Namyangju	10.74%	11.61%	10.23%	10.05%	11.78%	11.86%
Uijeongbu	12.65%	9.38%	7.73%	7.52%	7.75%	7.76%
Goyang	8.18%	7.58%	6.22%	6.11%	6.28%	5.99%
SCA	8.77%	8.21%	7.35%	7.17%	7.27%	7.16%

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-15. Trips by Whole Mode from Outside of Seoul to Seoul

(Unit: trip/day)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	753,220	753,374	740,604	785,140	821,127	835,353
Suwon	911,870	926,918	901,786	936,315	916,108	931,172
Seongnam	573,824	578,926	561,557	584,891	590,541	611,031
Namyangju	408,937	476,663	481,781	505,955	487,325	506,060
Uijeongbu	248,962	239,110	237,744	247,291	239,778	244,885
Goyang	378,067	445,591	416,250	431,060	433,689	445,764
Subtotal	3,274,880	3,420,582	3,339,722	3,490,652	3,488,568	3,574,265

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-16. Modal Sharing Ratio of Public Transport for Trips from Outside of Seoul to Seoul

(Unit: %)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	49.65%	45.35%	49.59%	51.13%	54.15%	54.07%
Suwon	48.54%	48.02%	52.43%	53.49%	54.14%	55.96%
Seongnam	45.65%	47.91%	51.12%	52.06%	53.54%	55.29%
Namyangju	33.55%	33.65%	40.35%	42.37%	40.40%	42.10%
Uijeongbu	45.28%	47.07%	51.48%	52.72%	52.72%	54.10%
Goyang	40.77%	40.48%	46.69%	47.02%	47.95%	49.85%
Subtotal	45.27%	44.36%	49.05%	50.26%	51.25%	52.55%

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-17. Commuting to Work Trips from Seoul to Outside of Seoul

(Unit: trip/day)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	93,339	99,698	135,056	145,701	146,592	148,501
Suwon	126,188	159,111	172,623	187,523	186,656	190,129
Seongnam	52,714	71,767	85,551	91,405	92,452	96,710
Namyangju	48,171	56,999	100,467	104,005	99,842	101,310
Uijeongbu	34,631	34,800	42,107	44,510	46,471	45,750
Goyang	56,151	56,475	81,827	88,126	92,150	96,255
Subtotal	411,194	478,850	617,631	661,270	664,163	678,655

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

Table A4-18. Whole Trips from Seoul to Outside of Seoul

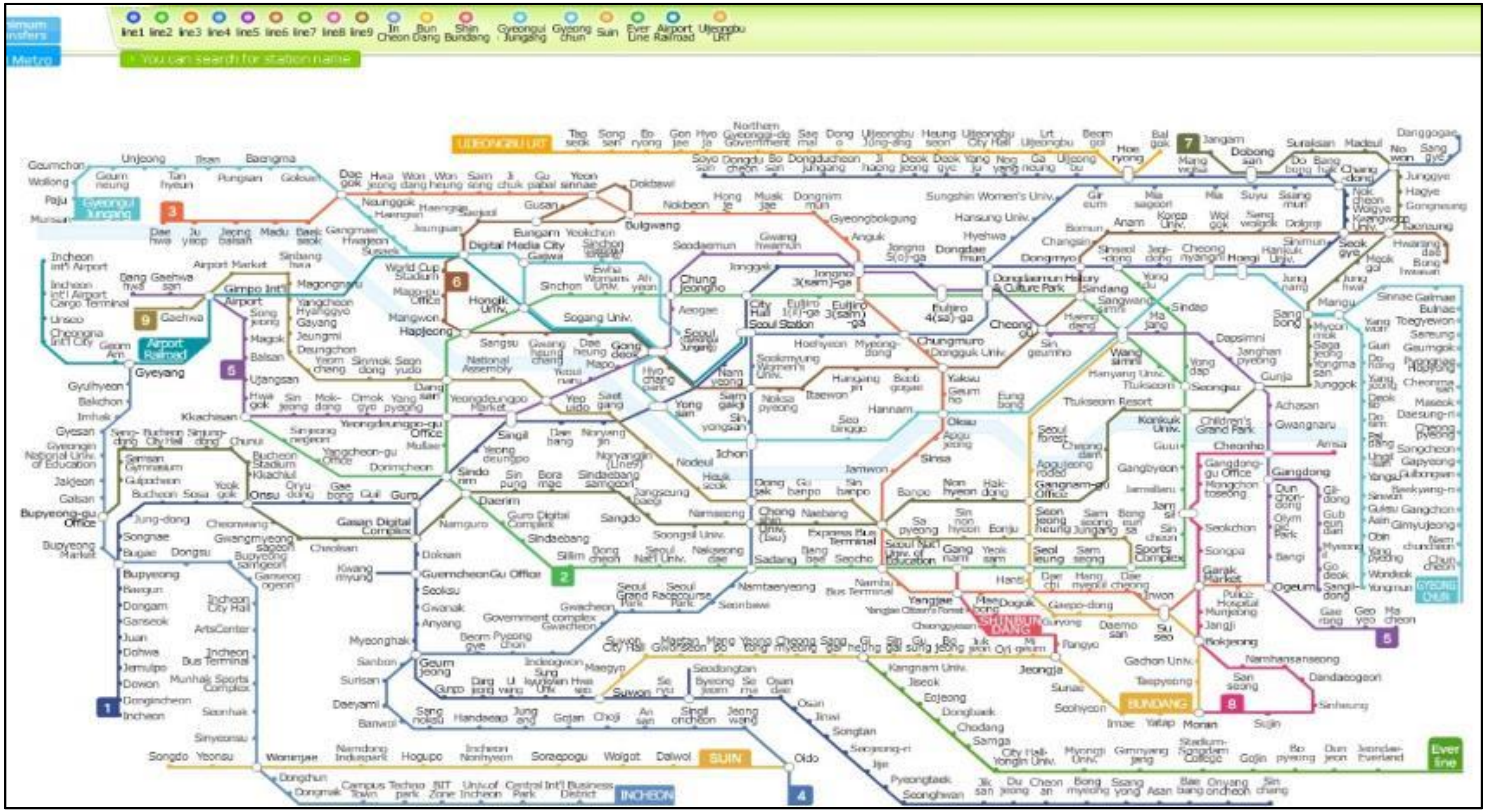
(Unit: trip/day)

Transport Axis	2002	2006	2010	2011	2012	2013
Incheon	240,452	248,522	288,128	303,576	311,975	316,991
Suwon	359,871	418,930	394,345	417,125	410,300	415,606
Seongnam	179,350	214,732	220,001	231,144	238,078	240,380
Namyangju	133,876	151,343	216,683	222,626	215,976	222,039
Uijeongbu	99,718	81,102	96,291	101,567	103,654	103,498
Goyang	138,523	131,568	167,473	177,587	180,037	188,946
Subtotal	1,151,790	1,246,197	1,382,921	1,453,625	1,460,020	1,487,460

Source: 2014 Revision of Origin/Destination Data in Seoul Capital Area (adapted)

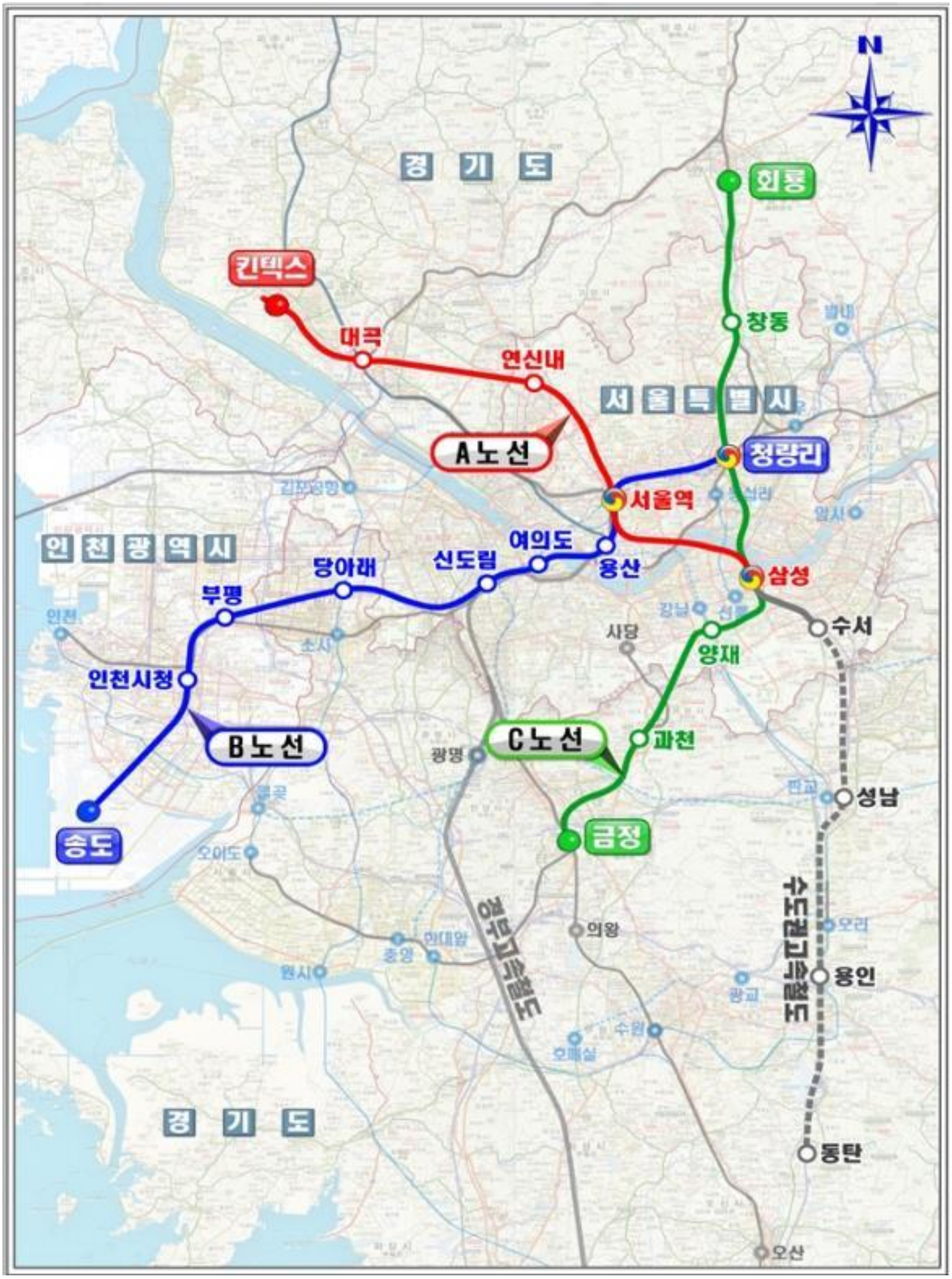
Appendix 5. Additional Figures

Figure A5-1. Line Map of Subway in THE SCA



Source: google (adapted)

Figure A5-2. Master Plan of Metropolitan Express Railway



Source: google (adapted)

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