URBAN CHANGE AND TRANSPORTATION VULNERABILITY TO EARTHQUAKES: THE CASE OF METRO VANCOUVER

by

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Abstract

A convergence of several factors has made Metro Vancouver's transportation system vulnerable to earthquakes. Unfortunately, traditional post-disaster evaluations are often inadequate as they undervalue regional dimensions of transportation quality. After a fairly basic examination of ten of Metro Vancouver's critical pieces of bridge infrastructure, results suggest that the transportation system will perform reasonably well when exposed to earthquakes with magnitudes between 4 and 8. However, certain damage outcomes leave many areas with limited accessibility. In particular, the simple sampling analysis suggests that the four most frequent damage outcomes - the loss of the Lion's Gate, Oak Street, Arthur Laing, and Alex Fraser Bridges, respectively - present some interesting results. The Oak Street and Arthur Laing Bridge damage outcomes appear to cause minimal travel disruption likely due to relatively high levels of network redundancy. Conversely, the loss of the Lion's Gate Bridge produces relatively much harsher diminished transportation performance. Furthermore, after observing transportation performance over time between 2004 and 2021, it would appear the region is at risk of suffering from diminished transportation quality as a consequence of land-use changes. These could have significant social and economical consequences. Overall, perhaps the most valuable output of this research is the formulation of a methodological framework to study post-earthquake transportation performance in Metro Vancouver. Another novelty of this research is the comparative study of earthquake risks in past and future regional environments. The paper also proposes some new methods for reducing post-earthquake transportation disruption. In particular this research suggests the use of targeted transportation demand management (TDM) policies to reduce strain on transportation networks prior to and following an earthquake. These are policies that could be included in municipal or regional disaster management and transportation planning frameworks.

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Acknowledgements

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Chapter 1. Introduction

1.1. Research Purpose and Objectives

This thesis addresses risk from natural disasters in the context of dynamic regional systems. Urban and regional systems are in a continuous state of flux. This is clearly observed through the growth, decline, and distributional shifts of population and employment centers, as well as through direct urban infrastructure alterations (e.g. addition of a bridge). Despite this widely accepted observation, disaster research is seldom discussed within the context of urban or regional change. Surely the way we study, view, and plan for a disaster is dependent on how areas change, especially considering that even modest alterations to the regional form can produce significant variations in the outcome of a disaster.

The direction and degree of transformation cities experience are, at their core, typically controlled by land-use regulations. Within the field of urban planning, it is understood that the land-use configuration of a city is a fundamental component, which influences nearly every urban activity. What this research hopes to highlight is the importance of land-use in both transportation and disaster contexts. More specifically, this research proposes that regional form and the way cities are designed affect transportation-performance risk following an earthquake. Therefore, Metro Vancouver's land-use configuration is a central element of this work[1].

Given the tectonic setting the region is currently in, Metro Vancouver has a serious risk to earthquake hazards. In fact, over the next 10 years research suggests that there is a 2.5% probability that a structurally damaging earthquake could strike Metro Vancouver. Over the next 50 and 100 years, this probability increases to 12% and 22%, respectively (Onur and Seemann, 2004). What is also concerning is that due to Metro Vancouver's unique geography, it relies on a suite of bridges. Unfortunately, previous disasters have demonstrated that this type of infrastructure is particularly vulnerable to earthquake hazards (Chang and Nojima, 1997; Giuliano and Golob, 1998; Chang and Nojima, 2001). Transportation infrastructure is critical for this growing metropolitan and hundreds of thousands of its commuters.

The over-arching objective of this research is to understand how regional form (or 'regional land-use configuration') contributes to transportation performance in natural disasters, now and in the future. This study involves several sub-objectives:

[1] Regional form, regional land-use configuration, land-use configuration, and land-use are terms used interchangeably throughout this thesis. Typical definitions of 'land-use' include some reference to the type of development, lot width, lot area, setback, building height, density, lot coverage, and even tone and design of development; for this research, 'land-use' simply describes the population and employment characteristics of geographic zones throughout Metro Vancouver.

1. Develop a methodology for evaluating post-earthquake transportation performance.
2. Understand how transportation systems will perform in various earthquake scenarios.
3. Understand how post-earthquake transportation performance risk behaves over time.
4. Determine which areas in the region are subject to the greatest transportation risk.
5. Determine which pieces of transport infrastructure are most critical to minimizing risk.
6. Determine which land-use configurations pose the least post-earthquake transportation disruption.

It should be noted that the scope of the study is limited to earthquake hazard risk in Metro Vancouver, British Columbia. With respect to these objectives, this research will show that:

1. The general methodological framework presented in Section 3.2 consists of a hazard, bridge structural, and transportation model, which can be used to determine post-earthquake transportation performance. Though this research takes a 'sampling approach', the general methodological framework developed lays the foundation for other types of analysis in the future (e.g. FORM Analysis; see Section 5.4.4).
2. Based on this simplified methodological framework, Metro Vancouver's transportation system seems to perform reasonably well when exposed to sub-crustal earthquakes with magnitudes between 4 and 8. Overall, for the sample of potential earthquakes studied, there is an 85% chance that no bridges will experience significant damage (Chapter 4).
3. In most earthquake damage outcomes, the way Metro Vancouver's land-use configuration evolves between 2004 and 2021 will make earthquake hazards in the future more serious.
4. Among the most frequent damage outcomes, diminished transportation appears to affect North and West Vancouver most severely, due to relatively lower levels of network redundancy.
5. Of Metro Vancouver's transportation infrastructure, it would appear that the Lion's Gate Bridge is most critical to minimizing travel disruption. Furthermore, due to certain changes to Metro Vancouver's regional form, the Alex Fraser Bridge also appears to be critical in the future as its own bridge usage increases.
6. Certain land-use configurations put less strain on transportation infrastructure; these configurations are optimal for minimizing future post-earthquake transportation disruption.

1.2. Research Relevance: Lessons Learned from Previous Hazards

An immediate question that arises is 'considering all the potential consequences an earthquake may pose, why study transportation systems?' Transportation systems are critical

pieces of infrastructure for any city or region. Studies have demonstrated that transportation systems touch nearly every urban activity in some way (Meyer and Miller, 2001). Moreover, in a disaster context, these systems have been shown to be particularly vulnerable. When studying our history of disasters, three events more than any other have demonstrated the catastrophic toll earthquakes have had on transportation systems. With varying degrees of devastation, they include the 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes.

The Loma Prieta earthquake, which struck on October 17th, was the largest earthquake to hit the San Francisco Bay Area in over eighty years (magnitude 7.1). In particular, damage to 91 state highway bridges (13 closures) caused major transportation disruption. However, the most significant damage occurred on the San Francisco-Oakland Bay Bridge, forcing its closure for one month (Chang and Nojima, 2001). The Northridge disaster was the costliest earthquake in American history. This 6.8 magnitude quake struck the Los Angeles suburb of Northridge on January 17th (Chang and Nojima, 1997). Fortunately, fatalities were limited; however, destruction to many pieces of transportation infrastructure was significant. In total, 286 state highway bridges were damaged. Notably, the disaster severed connections on four major freeway links (Interstate-5, State Route-14, State Route-18, and Interstate-10), leaving many growing suburban areas isolated from the rest of the region (Chang and Nojima, 1997). The Kobe disaster was considered to be the most economically destructive earthquake of the 20th Century. Occurring exactly one year after Northridge, the Kobe earthquake struck a narrow, densely-populated urban corridor some two kilometers wide, situated between extensive northern mountain ranges and Osaka Bay (Horwich, 2000). The magnitude 7.2 JMA (Japan Meteorological Agency) earthquake caused significant damage estimated at US$100 billion, affecting the port-city of Kobe's roughly 1.5 million residents, as well as other neighboring cities. Extensive damage was seen to both rail and Kobe's regional highway system (Horwich, 2000).

Clearly, the loss of transportation systems could have devastating social and economic implications to a region (and its population). To contextualize the potential effects an earthquake could have on Metro Vancouver's transportation network, let us observe a recent event. In early 2009, the unexpected closure of the Pattullo Bridge, a moderately utilized bridge in Metro Vancouver, 'created havoc for rush-hour commuters'[2]. The closure caused significant disruption for many commuters, and illustrated how the unpredictable loss of even a single piece of urban infrastructure could have very disruptive consequences. In preparing for hazardous events, hopefully this research can assist city planners choose an optimal land-use configuration that

[2] http://www.cbc.ca/canada/british-columbia/story/2009/01/26/bc-pattullo-bridge-reopens.html

would minimize risk. Other applications include assisting decision-makers in pre-disaster retrofit prioritization and post-disaster repair strategies.

Chapter 2. Research Background

This chapter provides background and context for the study. Specifically, it will include a review of relevant literature found in the transportation, land-use, and disaster management planning disciplines.

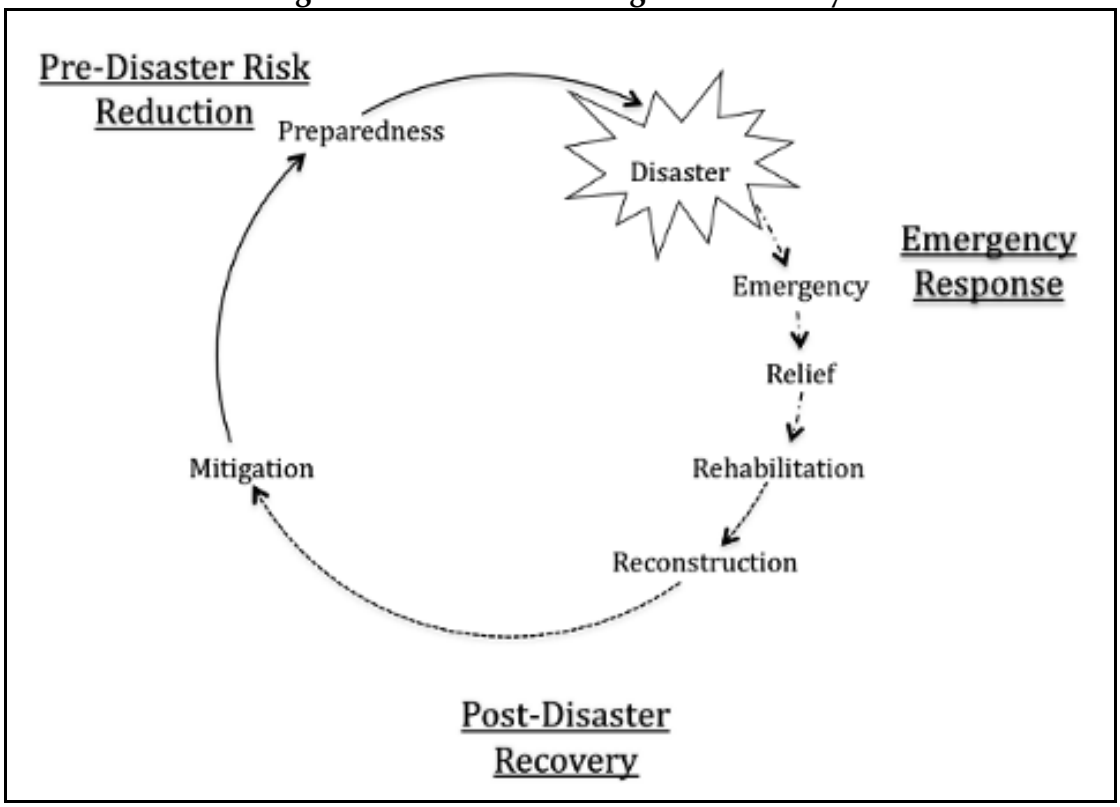
2.1. Literature Review

The main purpose of this section is to review selected literature that reflects the breadth of research previously accomplished in the field. A review of existing literature in the overlapping fields of transportation, land-use, and disaster planning will be useful to help identify which potentially unexplored paths of research can be pursued. Overall, it will cover literature examining (1) the interaction between land-use and natural disasters, (2) the interaction between land-use and transportation, and (3) post-earthquake travel behavior.

2.1.1. Land-Use and Natural Hazards

The importance of land-use to help stave off disaster became apparent more than half a century ago, when regulations were put in place to prevent development on flood-prone lands. Under the simple argument that "flood losses could be reduced significantly if, rather than trying to keep the flood out of people's way, government worked to keep people out of the flood's way by discouraging development of hazardous areas" (Burby, 1998; see also Burby and French, 1981; Godschalk, Kaiser, and Berke; 1998; Olshansky and Kartez, 1998; Mileti, 1999). It seems like a very logical notion, however individuals and decision-makers continue to put themselves in dangerous circumstances, accept the possible risk, and rely far too much on traditional coping mechanisms. In particular, an overreliance on what researchers describe as the cycle of pre-disaster risk reduction, emergency response, and post-disaster recovery (Figure 2.1), can encourage individuals to make ill-advised decisions with respect to where they live (Schwab et al., 1998; Zhang, Okada, and Tatano, 2006; Haddow, Bullock, and Coppola, 2007).

Figure 2.1: Disaster Management Risk Cycle



Source: after Zhang, Okada, and Tatano, 2006

Burby (1998) argues that these traditional coping mechanisms are inadequate. For one, warning systems have varying degrees of effectiveness, as they are often underappreciated, completely ignored or not adequate. A warning system for a hurricane may properly inform the public of pending calamity, whereas warning systems for earthquakes are not nearly adequate enough to provide proper notification. Another argument against these traditional coping mechanisms is that relief and insurance mechanisms often encourage individuals to willingly and recklessly accept certain risks, with the expectation they will be properly compensated if a disaster were to occur. Having these mechanisms in place creates this safety net and lulls individuals into a false sense of security. Coupled with the infrequency of some hazards, individuals can become complacent. As a result, they may not take the proper precautions to reduce their exposure to the hazard. Burby (1998) lastly argues that making structural improvements (e.g. levees, bridge retrofitting) to mitigate the effects of a hazard can be very costly. Furthermore, since many individuals feel these structures provide complete protection against risk, development on vulnerable land often occurs. Unfortunately, when a disaster is able to exceed specific design limits, the outcome of the disaster becomes far more severe than it would otherwise have been (Burby, 1998).

Burby (1998) argues the solution to these problems exists in proper land-use. The definition of land-use typically encompasses several elements. They include the type of development (e.g. residential, commercial, industrial, institutional, recreation, and environmental), lot width, lot area, setback, building height, density, lot coverage, and even parking provisions. Essentially, each of these elements fall into two land-use management approaches, each of which can help reduce exposure to risk. They include a locational approach and a design approach. The former approach 'tends to be effective in reducing losses, preserving environmental values, and providing opportunities for outdoor recreation' (Burby, 1998). This approach does however reduce some economic benefits that could be gained by locating on hazardous lands. The design approach is 'safe construction in hazardous areas'. This allows some of the economic benefits to be realized, while still reducing risk. Overall, it is suggested that there be a proper mix of both approaches.

Though land-use regulations to reduce risk seem logical, there are many barriers that have prevented this type of risk-averse action to take place. For one, there is a lack of commitment from decision-makers. Local governments are often not mandated by higher-level authorities to accept such measures. As a consequence, hazards are given little priority behind more urgent local interests including crime, housing, education, and even unemployment (Burby, 1998). There are management limitations, especially in identifying vulnerable areas, which also prevent land-use measures from being employed. Non-compliance of developers, builders, and landowners has also hindered progress, especially without stringent enforcement by local governments. Lastly, there has been a lack of regional land-use coordination when handling disasters (Burby, 1998).

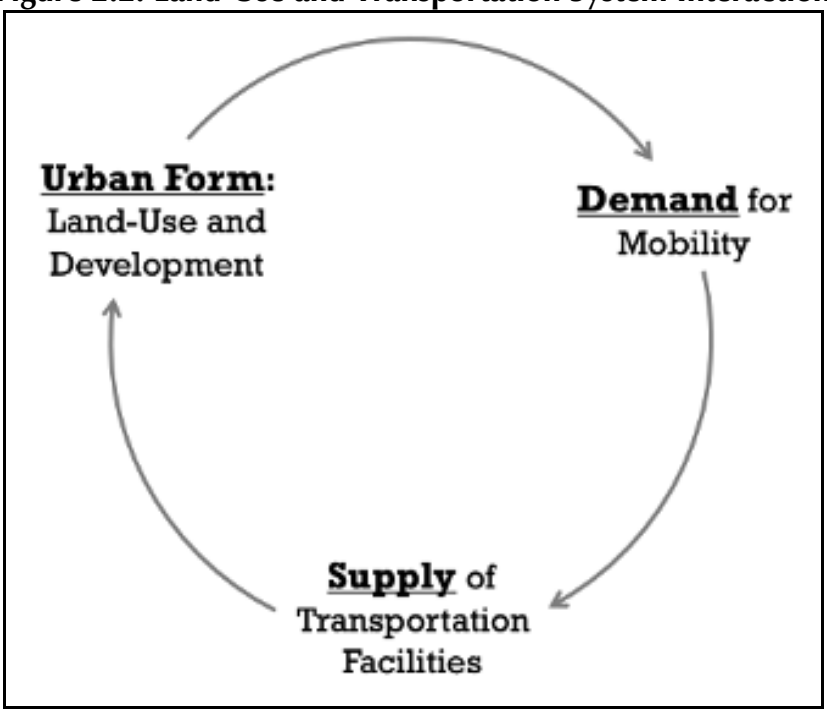
Land-use planning is an extremely piecemeal process, and often as a consequence we fail to see the hazardous implications of some of the decisions made years and sometimes decades ago. Clearly there is a linkage between how urban planners control land-use and exposure to hazard risk. If greater emphasis is given to land-use, perhaps risk can be reduced to help maintain regional sustainability.

2.1.2. Land-Use and Transportation Systems

Strong interdependencies exist between both land-use and transportation, and consequent travel patterns. As Meyer and Miller (2001) discuss, "the linkage between land-use and transportation is a fundamental relationship in the study of transportation. Put simply, the trip-making characteristics of a region – spatial travel patterns and modal distributions – are largely a function of how land is organized and used" (p. 128). Transportation investments, such as the expansion of highway networks, have also altered land-use and travel patterns. For instance, the expansion of highways allowed populations to decentralize and the urban fringe began to grow.

The greater dispersion to areas with poor transit networks often encouraged automobile dependency. Meyer and Miller (2001) discuss the relationship between transportation and land-use as being complicated. Land development patterns for an urban area often dictate where businesses and households are located. As a result, there is often subsequent development of facilities such as schools, shops, and recreation sites. Consequently this newly formed land development will now create trip-making, travel demand, and an eventual need for a means of transportation. Overall, "increased accessibility and improved land values, in turn, influence the location decisions of individuals and firms, once again spurring new land development and starting this cycle again, until an equilibrium is reached or until some other external factor intervenes" (Meyer and Miller, 2001). Hanson and Giuliano (2004) further discuss the relationship between land use and transportation. They state that both are mutually dependent. For instance, transportation will influence the ease or accessibility individuals have in moving between locations. This influences the location of activities (i.e. land-use) which alters daily activity patterns. This subsequently impacts transportation. This relationship is visually represented in Figure 2.2.

Figure 2.2: Land-Use and Transportation System Interaction



Source: after Meyer and Miller (2001); Hanson and Giuliano (2004)

2.1.3. Post-Earthquake Travel Behavior and Outcomes

The sudden loss of major transport facilities (such as in a natural disaster) can produce a myriad of commuter behavior responses, from simply changing travel route, mode, time, or

destination, to reducing trip-making frequency and trip-chaining. In severe circumstances, limited transport supplies can even diminish the incentives of car ownership or influence residential and employment location (Deakin, 1991). In extreme events, the loss of major transport facilities becomes of great concern to commuters and the region as a whole. Few instances have demonstrated this better than the aftermath of an earthquake. In particular, the 1994 Northridge quake presented an interesting opportunity to observe travel behavior response to drastic reductions in network supply, as four major freeways experienced significant damage. In fact, as Schmitt (1998) describes, "the Northridge earthquake and its aftermath provided a natural laboratory to examine travel behavior, the reliability of the transportation system, and the impact of transportation disruptions on businesses and the regional economy". Immediately following the disaster, transportation authorities began setting up detours and began forming a reconstruction plan (Giuliano and Golob, 1998). In the subsequent weeks, commuters experienced unpredictable travel conditions "as roads reopened, additional transit service was deployed, and detour routes were refined" (Giuliano and Golob, 1998). Only after approximately five months were all four freeways reopened to traffic.

This extended closure of major road infrastructure caused significant disruption to regional, and to a lesser degree, world economies. As Gordon et al. (1998) estimate, the total business losses cost more than $6.5 billion. Roughly $1.5 billion was a consequence of four types of travel disruption: (1) commute disruption which impeded travel from place of residence to work, school, etc., (2) reduced customer access, (3) disruption to shipping exports, and (4) disruption to shipping imports (Gordon et al., 1998). Focusing on the two former types of travel disruptions, Giuliano and Golob's (1998) examination of extensively damaged highway corridors found that for the most part, commuters responded to this transport disruption by choosing to change their travel route, travel time, and destination, and generally stayed automobile-reliant. Though some used rail initially after the quake, they reverted back to private automobiles when detours became available. However, considering these intensely sprawled areas are extremely automobile dependent, perhaps it was not a large surprise that people resorted to their vehicles once moderate restoration occurred. Nonetheless, these travel responses were a direct effect of the high level of network redundancy and flexibility on the part of the commuters.

In a similar way, the effects of the 1989 Loma Prieta quake were lessened by the high network redundancy; however, commuter flexibility was limited. Employers were less receptive to varying times of travel, but in general the region managed to minimize the effects (Deakin, 1991). The primary exception was the closure of the San Francisco Bay Bridge caused by the collapse of an upper deck. The closure had the potential to cause large-scale regional transportation

disruption since the bridge served 245,000 vehicles and roughly 400,000 individuals daily. The lack of alternative routes in the same direction as the bridge and virtually no detours were another source of major concern to commuters. Fortunately, the Bay Area Rapid Transport (BART) system had kept its structural integrity, and greatly reduced the impact to travelers as a viable mode. As a result, SOV, HOV, and transit ridership dropped 27, 25, and 9 percent respectively, while the BART usage grew 40 percent (Deakin, 1991). The overriding travel behavior outcome of the earthquake was a switch in mode usage for commuters who traversed the bridge. However, once repairs began and roads became serviceable, many commuters returned to their private vehicles. In general, system redundancy was a major alleviator of the earthquake-related transport disruption, except in the case of the Bay Bridge closure.

Given the travel behavior observations from prior studies, our research assumes a similar post-earthquake response, where damaged to specific links will compel travelers to alter their route choices. As the previous studies have demonstrated, this is facilitated by network redundancy. In our model this process can be represented in the final step of the transport model (Trip Assignment, see Section 3.2.3.2.d). These examined studies help validate our assertion that travelers will make changes to their routes, which can be reflected in our transportation model. Furthermore, they suggest that travel response varies by post-disaster phase, and that while major behavioral changes occur in the initial emergency response phase, the response stabilizes in the "rapid restoration" phase, typically several weeks after the quake when restoration is in progress (Chang and Nojima, 1997). Therefore, this research makes the assumption that the transportation system is representative of travel conditions during the restoration and/or recovery phases of the disaster management risk cycle.

Chapter 3. Research Methodology

This study is concerned with how the regional form or regional land-use configuration, can contribute to transportation risk following an earthquake. In describing the research methodology, this section will (1) introduce the data sources and specialized modeling software used, (2) provide an in-depth description of the three main sub-models framework (i.e. hazard, structural, and transportation), (3) describe the main outputs of the research, and (4) discuss how these outputs will be analyzed to assess transportation risk (i.e. sampling analysis).

3.1. Data Sources and Modeling Software

3.1.1. Transportation Data Source

TransLink, officially referred to as the South Coast British Columbia Transportation Authority, was the partner organization for this research project. Furthermore, this organization has provided our research with all the data required to examine post-earthquake transportation performance in Metro Vancouver.

TransLink is responsible for the planning, management, and financing of virtually all of Metro Vancouver's transportation activities and infrastructure[3] (e.g. major roads, bridge, and transit). It also maintains Metro Vancouver's transportation model. Obtaining all the data required to model the region's transportation system has been an exhaustive undertaking for TransLink; one that has taken several years to complete. Much time and effort went into developing the model, and it has been an invaluable tool for decision-makers, as it provides insight in many of the region's transportation and land-use projects. The model contains land-use and road network data for Metro Vancouver's transportation system, specifically for 2004 and projected 2021 study periods. For the purposes of this research, using a transportation model that is currently being employed by Metro Vancouver and TransLink adds assurances that the original data being analyzed is accurate. However, it should be noted that in order to replicate post-earthquake transportation conditions, some of this data will be manipulated. For instance, to mimic road closures as a consequence of an earthquake, the number of lanes on specific links will be reduced.

[3] http://www.translink.ca/en/About-TransLink.aspx

3.1.2. EMME/3 Transportation Modeling Software

As mentioned previously, TransLink has compiled an immense amount of data. This includes travel diaries, commuter surveys, and traffic counts, as well as population and employment data. In the past, due to computational limitations it would have been infeasible to model a large urban environment's transportation network. However technological advances currently allow for complicated modeling to occur with limited problems. To model Metro Vancouver's transportation system, TransLink utilizes the software package EMME/3. EMME/3 is a state-of-the-art transportation forecasting model, developed initially in the 1970's as an experimental code by a research group at the University of Montreal (EMME, 2007). The software's name is in reference to a multimodal equilibrium, which is a central element to how the model works. Building on previous versions, the latest EMME software still includes a powerful script-based interface that allows the user to perform large data calculations common in transportation modeling. However, the addition of an interactive graphical user interface (GUI) now effectively allows many of the post model outputs to be visually represented. Today the software is used around the world in major metropolitan areas for both large and small transportation modeling tasks.

As a technical note, data such as land-use and travel cost enter the software as a representation of one of four data configurations: full matrix (mf), origin matrix (mo), destination matrix (md), or scalar matrix (ms). A full matrix contains zonal O-D data, typically of travel time or volumes. Origin and destination matrices contain land-use data for their respective origins and destinations. Finally, scalar data is a single value, often used to adjust other matrices.

3.1.3. Reliability Tools ('Rt')

With software developed by Mahsuli and Haukaas (2010) referred to as Reliability Tools or 'Rt', all the individual modeling tasks are brought together. The software is a very flexible graphic interface that allows users to create hazard, infrastructure, and consequence models by defining specific model variables. The software was motivated by the premise that probabilistic models have uncertainty associated with them (Mahsuli and Haukaas, 2010). Thus, uncertainty enters the models typically as 'random variables'. A typical model will utilize (1) inputs from an upstream model and (2) the realizations of random variables as seen in Section 3.2 (Mahsuli and Haukaas, 2010). Overall, the Rt software provides the user with a range of model options to test a myriad of hazard scenarios. In particular, the software offers the use of reliability methods and sampling; the later of which will be utilized in this research.

3.2. General Methodological Framework

Evaluation of post-earthquake transportation performance for this research is conducted under the general methodological framework represented in Figure 3.1. As illustrated in this figure the methodological framework consists of (1) a hazard model, (2) a bridge structural model, and (3) a transportation model, each of which will be discussed in further depth in this section. It should be noted that random variable inputs enter into the hazard and structural models (Table 3.1). The figure also indicates that under this general framework, it is possible for random variables to enter the transportation model (represented by the dashed arrow). However for this research random variables will not enter the transportation model. Rather, using a sampling methods tool offered by Rt, the hazard model will generate 10,000 earthquake realizations after various model characteristics are defined (e.g. magnitude, location, etc.). The output of the hazard model is an intensity measure used by the bridge structural model. The structural model will determine the mostly likely 'bridge damage outcomes' by calculating a bridge's 'percent functionality'. This information feeds into the transportation model. Ultimately, the final output is a transportation performance indicator (TPI).

Figure 3.1: General Methodological Framework

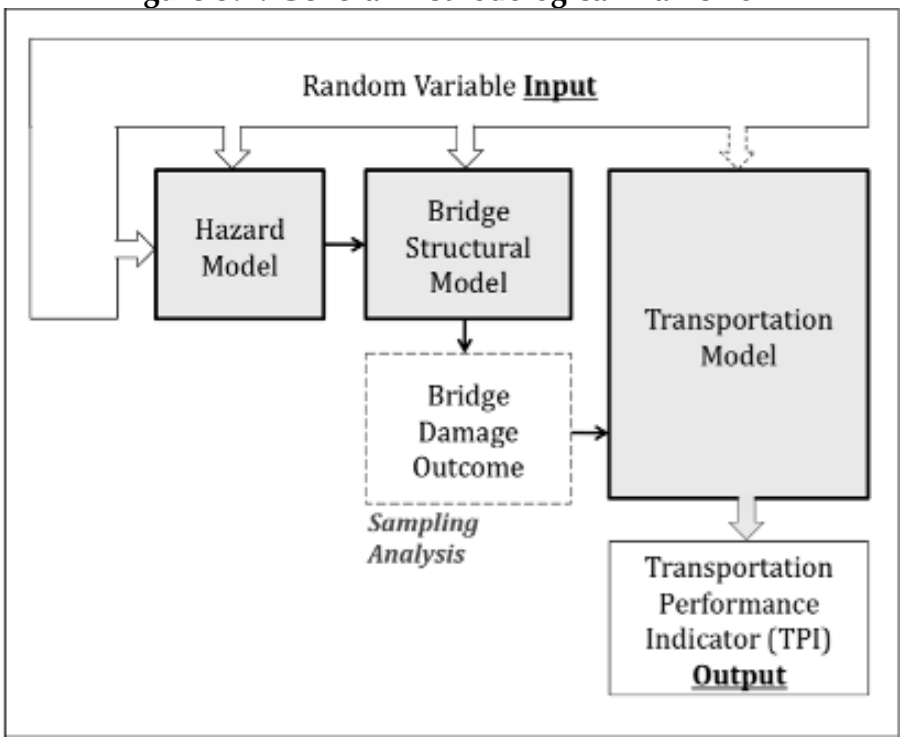


Table 3.1: Random Variable Model Inputs

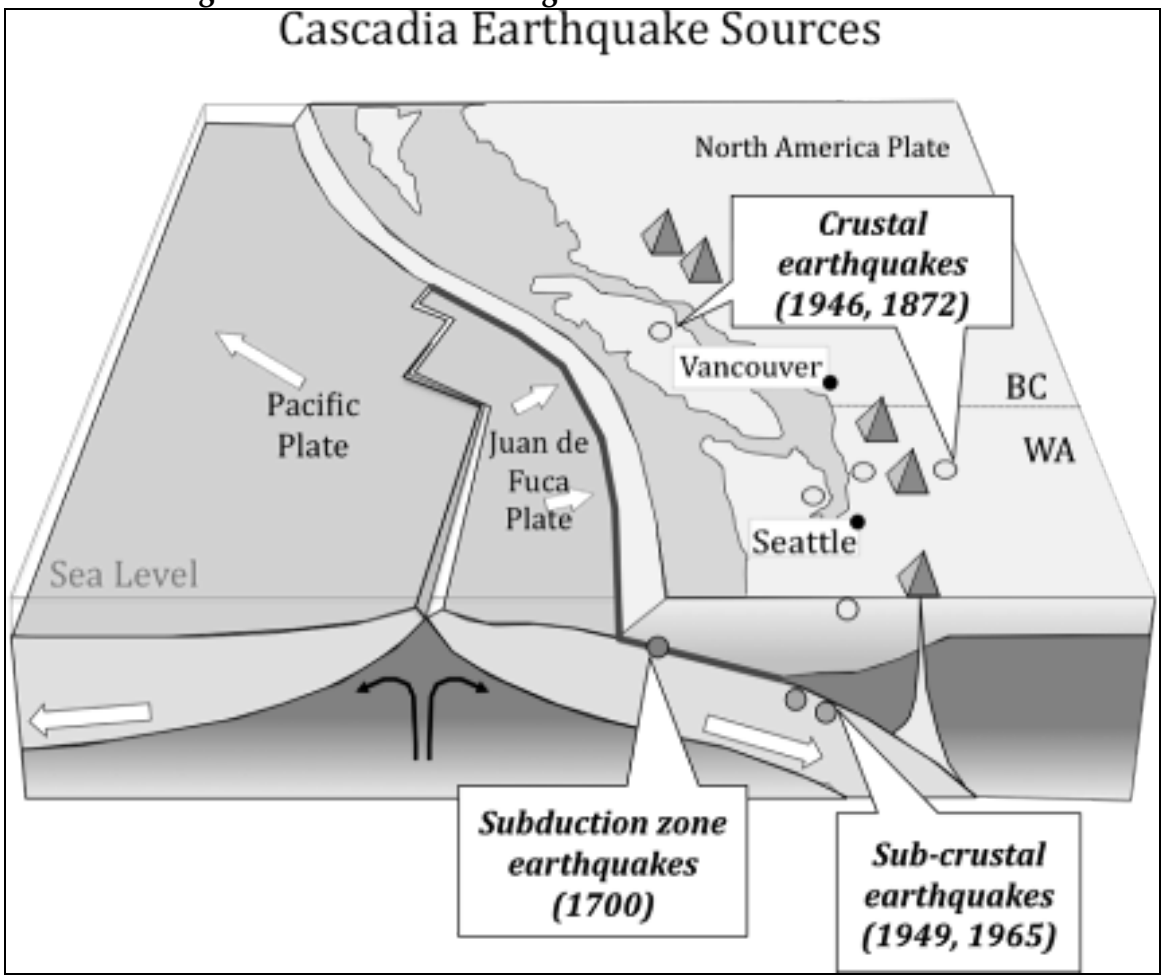
Model	Random Variable(s)
Hazard Model	-Magnitude -Location -Depth
Bridge Structural Model	-Bridge Percent Functionality

3.2.1. Hazard Model

The tectonic setting and seismicity found in southwestern British Columbia have produced unique hazardous conditions. In particular, the Cascadia subduction zone located beneath the boundary between the oceanic Juan de Fuca Plate and the continental North America Plate (Figure 3.2) has the potential to produce three different types of earthquake hazards: 'mega-thrust' subduction zone, deep sub-crustal, and shallow crustal earthquakes (Onur and Seemann, 2004). Subduction zone earthquakes strike very infrequently, with reoccurrence periods between 500 and 600 years. In fact the last subduction zone earthquake to occur in this region was in January 1700 with a 9.0 magnitude. Sub-crustal earthquakes have a reoccurrence period between 30 and 50 years, and can reach magnitudes of 7.0 and greater. Similarly, crustal earthquakes can reach magnitudes of 7.0 and greater, however these hazards often strike more frequently, with a reoccurrence period approximately once every decade (Clague, 2001; Onur and Seemann, 2004).

Deep sub-crustal earthquakes, similar to the 2001 Nisqually Earthquake, could occur in the Metro Vancouver region with the potential to cause even greater damage than the event in Washington State (Clague, 2001). To test the potential impact this type of hazard will have on the region's transportation system, this research will limit its scope to sub-crustal earthquakes.

Figure 3.2: Tectonic Setting of Southwest British Columbia



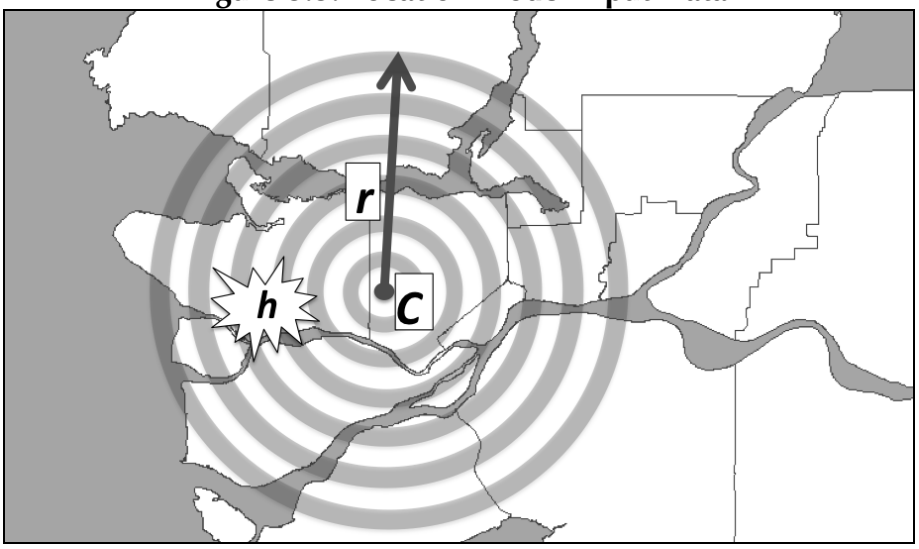
Source: after Clague, 2001

The hazard model used for this research is itself defined by magnitude, location, and intensity models. Focusing on deep sub-crustal earthquakes, many variables must be chosen. Research examining the seismicity of Southwest British Columbia suggests that sub-crustal earthquakes tend to have magnitudes ranging from 4 and 8 (Clague, 2001; Clague, 2002). Therefore, magnitude is treated as a continuous random variable with a bounded exponential distribution between 4 and 8.

The hypocenter location of a generated earthquake will occur within a circular area bound. The location characteristics of sub-crustal earthquakes are often comparable to 'floating earthquakes'. As several researchers have described, floating earthquakes are "events presumed to be possible at any location within the tectonic province" (Jansen, 1988; see also DePolo and Slemmons, 1990; Krinitzsky, Gould, and Edinger, 1993). To test the structural integrity of some of Metro Vancouver's bridge infrastructure, earthquakes will occur within a circular area having a center location (*c*) in mainland Vancouver and radius (*r*) of 90 kilometers, as seen in Figure 3.3.

Given that the intensity of an earthquake beyond a 90 kilometer radius is relatively negligible, it is fair to assume that earthquakes beyond this radius would be non-consequential to the bridge infrastructure currently being examined in this research (Atkinson, 2005). An earthquake generated by this sub-model will have a hypocenter location (*h*) that will occur within this delineated area. Finally, using an attenuation algorithm developed by Atkinson (2005) specifically for this region, the intensity model will determine the probable spectral acceleration (S_a), or intensity of shaking, at various bridge locations.

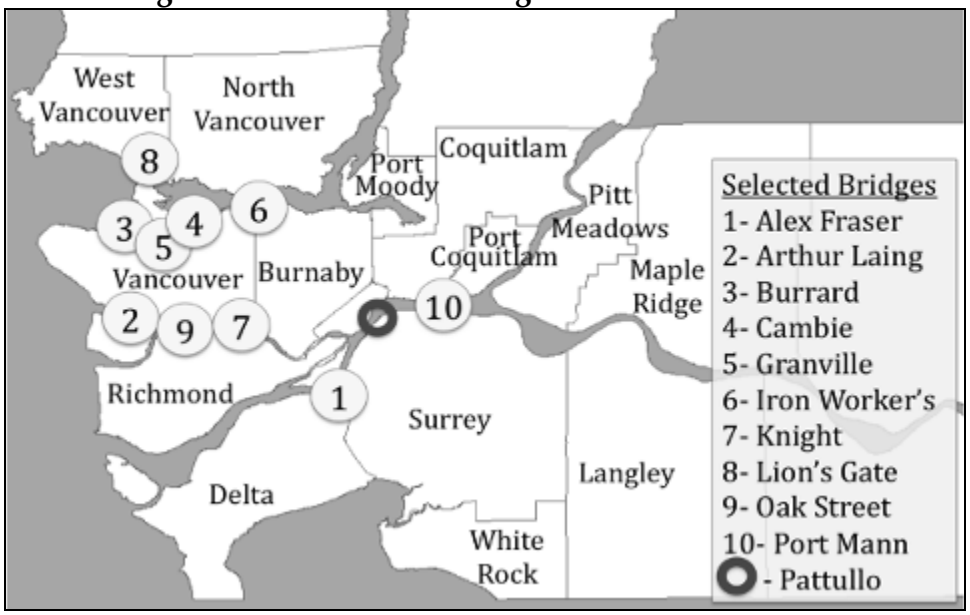
Figure 3.3: Location Model Input Data



3.2.2. Bridge Structural Model

Bridges, especially in a region like Metro Vancouver, are critical pieces of infrastructure. Due to Metro Vancouver's unique geography, particularly the amount of water bodies present, transportation users rely on an extensive system of bridges. Compared to other transportation infrastructure, bridges typically experience the greatest damage during an earthquake (Deakin, 1991). For this reason, it is assumed in this research that other road links such as at-grade infrastructure are not damaged. Certainly every bridge within the region is at risk of failure following an earthquake, but this research is limiting its scope to 10 of the region's most critical bridge infrastructure. They include the Alex Fraser, Arthur Laing, Burrard, Cambie, Granville, Iron Workers, Knight, Lion's Gate, Oak Street, and Port Mann Bridges seen in Figure 3.4.

Figure 3.4: Location of Bridges Under Examination

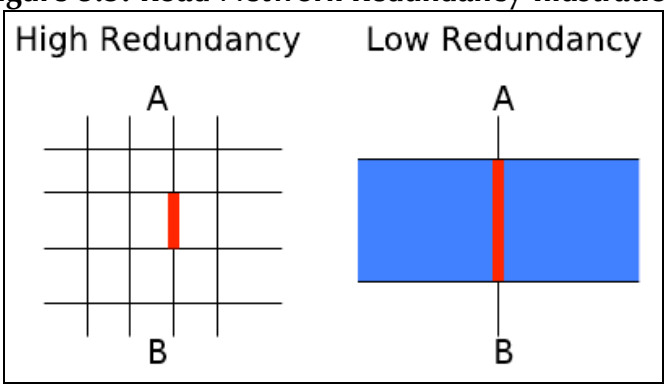


Due to several reasons these bridges are among some of the most critical pieces of infrastructure in the region. Firstly, each bridge helps maintain regional connectedness (Table 3.2). Often transportation users require travel across different regional sub-areas, thus making these bridges vital. Secondly, each bridge is contained within an area of low network redundancy. Each of these bridges spans across a water body. Since these structures are generally the only means to get over the water, the surrounding areas are considered to have a low network redundancy. As seen in Figure 3.5, if an area has a low network redundancy, users are restricted in the number of route options. Thus when a link is closed in a low redundancy area, greater travel disruption typically ensues. Lastly, among bridges in the region, these ten links experience high usage or daily traffic. Ultimately, smaller bridges such as overpasses, trusses, and viaducts were omitted from this research. Furthermore, these smaller pieces of infrastructure are likely less influential to the region's transportation system as they are associated with areas having higher network redundancy.

Table 3.2: Bridges Contributing to Regional Connectedness

Bridge	Regional Sub-Areas Connected by Bridge
Alex Fraser	Delta, New Westminster
Arthur Laing	Vancouver, Vancouver International Airport
Burrard	Vancouver, Downtown Vancouver
Cambie	Vancouver, Downtown Vancouver
Granville	Vancouver, Downtown Vancouver
Iron Workers	Vancouver, North Vancouver
Knight	Richmond, Vancouver
Lion's Gate	Downtown Vancouver, North Vancouver
Oak Street	Richmond, Vancouver
Port Mann	Surrey, Coquitlam

Figure 3.5: Road Network Redundancy Illustration



Each of the ten bridges have been assigned a structural model, which has used information (i.e. spectral acceleration) from the previous sub-model to determine the extent of damage a bridge would experience following an earthquake. Ideally, detailed structural models would have been developed specifically for each bridge. However, this would entail a significant amount of structural modeling work that is outside the scope of this study. Instead, simplified structural models developed for generic bridge categories were used. It should be noted that though some of the bridges under study in this research have been retrofitted, the structural models used do not account for these structural improvements (Please refer to Appendix A for list of retrofitted bridges).

A technical manual developed by the Department of Homeland Security, the Emergency Preparedness and Response Directorate, and the Federal Emergency Management Agency (FEMA) together with the National Institute of Building Sciences (NIBS) created various bridge structural models as part of the HAZUS loss estimation model (FEMA, 2003). Using a specific bridge classification scheme, data such as bridge type, skew angle, number of spans, and bridge length were required to determine which of the 28 possible classes each bridge would fall into (Please

refer to Appendix A for bridge data and classification). Given a specified spectral acceleration, each bridge model will generate a 'percent bridge functionality' random value that is required by the subsequent transportation model. It should be noted that the percent functionality of each bridge is a continuous number between 0 and 1. However, for reasons discussed in Section 3.2.3.1.a, the percent functionality value will be either rounded down or up to 0 or 1, respectively using a rounding threshold. Therefore, if a rounding threshold is set to 0.98, as it is in this research, a bridge's percent functionality below or above this value will be rounded to 0 or 1 respectively. What this model does is generate various bridge damage outcomes. The damage outcomes feed into the transportation model.

3.2.3. Transportation Model

The transportation model is the final sub-component within the general methodological framework. It should be emphasized that TransLink provided this research with the Metro Vancouver transportation model, which has been central to this thesis. The model produces results specifically for long-term transportation planning based on the concept of model equilibrium. This transport demand model forecasts peak AM travel, and is different from the previous two models as the results produced here are deterministic rather than probabilistic. Also it should be emphasized that this research is looking to predict post-earthquake travel behavior during the restoration and/or recovery phases, when travel is less chaotic and somewhat stable.

To fully understand and appreciate the significance of each modeling decision, assumption, and most importantly the final results, this section will need to thoroughly address several related areas. Altogether, it will (1) describe traditional and current uses of transportation models, (2) describe transportation modeling theory (3) describe the potential options for using the inputs from the structural model, (4) perform a model verification, and (5) evaluate various transportation performance indicators.

3.2.3.1. Traditional and Current Research Uses of Transportation Models

Transportation models are typically used for economic or engineering purposes, as a means to examine demand management, urban growth, or even transportation facility improvements. Generally the primary applications of transportation models such as this ultimately seek to answer one of two questions:

- How will travel conditions vary from changes to the travel system such as changes to the road network? OR
- How will travel conditions vary with a given developmental or demographic change? (Wang and Krajczar, 1998)

In either instance, this research will need to address these questions, as it will determine which changes to the urban environment are of greatest importance in influencing the potential consequences of an earthquake. In this respect, a transportation model is a powerful tool, however any user of the model or of its outputs must acknowledge that it cannot account for every possible variable, and at best is a simplification of reality. This considered, the model is most effective as a comparative analytical tool, particularly when examining the effects of varying earthquake scenarios (Wang and Krajczar, 1998).

In order to answer this research's principle questions, TransLink's Metro Vancouver transportation model will need to be manipulated beyond its normally intended uses. The technical details regarding alterations will be discussed in greater depth. Specifically alterations include changes to the road network to mimic a bridge closure following an earthquake. Other changes which need to be studied are those to regional land-use configurations as well.

3.2.3.1.a. Road Network Adjustment

The transportation model accepts as an input, the information describing the structural integrity of all ten bridges. Ideally, if a bridge is damaged and consequently closed, the link in the model would be removed completely, however due to some software limitations, this was not possible. As a result, only the 'link capacity' can be adjusted. The link capacity is a value between zero and one expressing the proportion of lanes available on a specific link. A value of 1 indicates that the bridge is structurally intact and that all of the lanes are available for use. Conversely, a value 0.1 (zero value is not possible within the model) would indicate the bridge is damaged and only one tenth of the lanes normally available, are now open for use. Theoretically, link capacities can be a continuous number between 0.1 and 1. Under this circumstance, a bridge could be partially open (e.g. 0.5 link capacity), however for this research, a binary (i.e. open/closed) link capacity was chosen. Ultimately it came down to one main reason why the binary capacity was chosen over the continuous capacity. The most compelling argument for a binary option is that in reality following an earthquake, government officials and decision-makers typically do not allow travel across a bridge unless there is complete certainty that the structure is intact (Chang and Nojima, 2001). Largely due to liability and safety concerns, bridges are not

normally partially open. For this reason, the binary approach to classifying bridge damage was seen as the most appropriate. If a bridge is considered damaged, based on the previous sub-models, then the bridge's link capacity is lowered to near-zero to represent a link closure. If a bridge is deemed to be structurally intact, it will be unaltered.

It should be noted that if commuters encounter a bridge with a link capacity of 0.1, travel across the bridge would not immediately cease. In fact, commuters will initially continue to travel over the bridge, however with every iterative step during the 'trip assignment' stage (See Section 3.2.3.2.d), the assumption is that as commuters begin to recognize that they are not gaining any utility from travel across the bridge, they will eventually find an alternate route. Ultimately we would like to see which links contribute to the greatest transportation disruption. If we can identify which links are most critical for preserving, then we can identify which bridges warrant retrofitting and hopefully develop a retrofit prioritization scheme.

3.2.3.1.b. Land-Use Changes

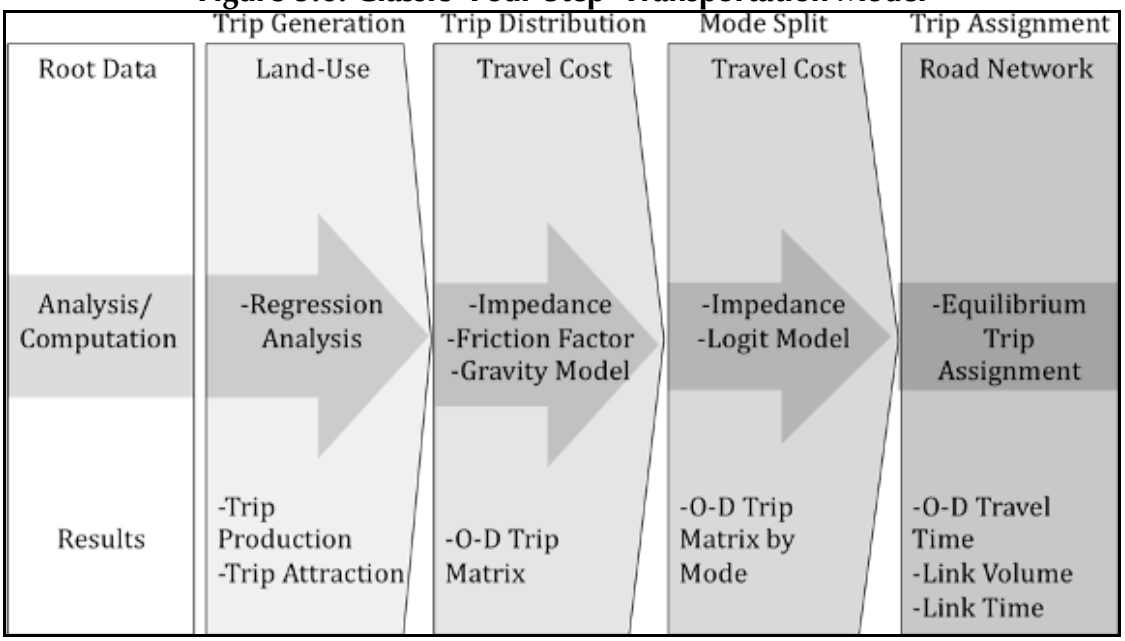
Land-use plays a central role to nearly all transportation issues, as illustrated in Section 2.1 (Literature Review). The type of land-use as well as the intensity of development are both variables which influence travel demand. For instance, if the City of Vancouver chooses to increase downtown employment density, (AM) travel demand to this area will likely increase. Given that land-use plays a role in normal travel conditions, it is this research's hypothesis that a region's land-use configuration contributes to transportation performance risk following an earthquake. Therefore, the degree of influence land-use holds within a disaster context needs to be determined. Two different land-use configurations exist in the model. Population and employment forecasts have allowed TransLink to generate two transportation models for 2004 and 2021. Each year represents a different land-use configuration as a consequence of changes to population and employment throughout the region. Under this option, a characterization of each land-use configuration scenario is required. For instance, each characterization will include a description of the type and location of population and employment in Metro Vancouver. Ultimately, under this option the outputs generated would be used to identify which land-use development contributes to the greatest transportation risk. If this is known, planners can use this information to construct an optimal planning scheme that would minimize risk to transportation systems following an earthquake. Considering that transportation activities directly or indirectly contribute to regional economies and social well-being, the outputs of this research may be relevant to urban planners and decision-makers alike.

3.2.3.2. Transportation Modeling Theory and Application to Metro Vancouver

Predicting travel demand has been of interest to transportation planners and engineers for nearly half a century (Meyer and Miller, 2001). And though technological advances, data acquisition improvements, and innovative analysis techniques have all made the process more efficient and accurate, the classic model structure, often referred to as the four-step or urban transportation modeling system (UTMS), has remained largely intact. This model has a mathematical bent, relying on a series of elegant formulae to describe complicated relationships from economic and consumer behavior theories and principles (Meyer and Miller, 2001). Overall, the model simply predicts the number of trips a zone produces, the travel destinations of these trips, the mode used (e.g. private automobile, transit, walking), and finally the probable route taken. Respectively, these tasks are preformed in sequence by the following sub-models: (1) Trip Generation, (2) Trip Distribution, (3) Mode Split, and (4) Trip Assignment. As indicated by the arrows in the background of Figure 3.6, one sub-model informs the next in the sequence. For the remainder of this section, each of these model components will be discussed in further depth with the aid of this figure. This figure describes how the primary model inputs (root data), in concert with several sophisticated analytical and computational techniques, can produce accurate travel forecasts.

It should be noted that this model forecasts travel during peak morning hours. Though in some instances after an earthquake, individuals chose to adjust their time of travel, it may be difficult to account for changes to commuters' travel schedule in this model (Giuliano and Golob, 1998). Despite this, forecasting travel disruption during AM peak periods can offer some insights, as this is when the transportation system is typically under the greatest stress (i.e. most commuters).

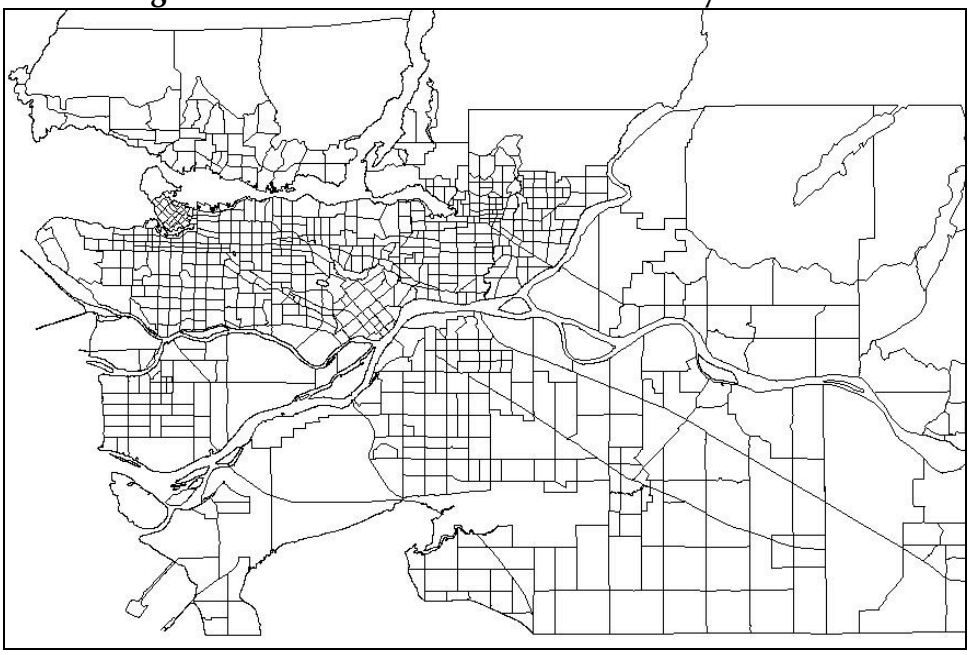
Figure 3.6: Classic 'Four-Step' Transportation Model



3.2.3.2.a. Trip Generation

The trip generation component of the UTMS uses various land-use data to attempt to predict how many trips a traffic analysis zone (TAZ) would generate. The Lower Mainland traffic zone system consists of 889 TAZs of varying size to reflect population and employment densities, and though normal zonal boarders may shift as a result, significant effort has been made to keep the existing census and municipal boundaries intact (Figure 3.7). Included among these traffic analysis zones are 21 park 'n ride zones as well as eleven external zones representing major access points to the system such as the Vancouver International Airport (YVR), US-Canadian boarder, and BC ferries.

Figure 3.7: Metro Vancouver Traffic Analysis Zones



Source: Wang and Krajczar, 1998

These nearly nine hundred zones are displayed on the digital base network through phantom nodes or centroids that allow land-use data (Table 3.3) to be loaded onto the network. Included within each land parcel are land-use data. The land-use data includes information related to population disaggregated by age, student enrollment, and employment.

Table 3.3: Origin/Destination Land-Use Data

Residential Land-use Data		**Non-Residential Land-use Data**	
Variable	*Description*	*Variable*	*Description*
mo12	1996 Average Hourly Wage	mo/md24	Elementary School Enrollment 5-12
mo/md13	Population Age 0 to 4	mo/md25	High School Enrollment 13-17
mo/md14	Population Age 5 to 12	mo/md26	Post Secondary Enrollment
mo/md15	Population Age 13 to 17	mo/md27	Employed Labor Force
mo/md16	Population Age 18 to 24	mo/md28	Employment Retail
mo/md17	Population Age 25 to 44	mo/md29	Employment Other (non-retail)
mo/md18	Population Age 45 to 64	mo/md30	Employment Total
mo/md19	Population Age 65 and over		
mo/md20	Population Total		
mo/md22	Population Not Employed		
mo/md23	Post Secondary Residence Students		

Using this land-use information, the number of trip ends generated by each zone is predicted. Trip ends fall within either trip production zones or trip attraction zones. To illustrate this point, consider the morning travel of a young working adult. During the morning trip, this person's home would be considered a production zone, whereas his work place would be

classified as the attracting zone. Every zone can potentially be a producing or attracting zone, thus when performing trip generation analysis, the trip purpose and study period must be identified (e.g. AM or PM peak). There are generally three classes of trip purpose: home-based work, home-based other, and non-home-based trips (Hanson and Giuliano, 2004). Home-based trips are journeys that either begin or end at home, whereas non-home-based trips neither begin nor end at home. For the Metro Vancouver transportation system, the trip generation model takes into account four possible peak morning (7:00 to 9:00 am) trip purposes: travel to work, travel to post secondary institutions, travel to grade schools, and travel to other destinations (e.g. family, shopping). This considered, separate trip production and attraction calculations are needed for each of these travel purposes. Trip generation formulas, in this case performed through multi-regression analysis, are a product of sub-regional trip rate records (from travel survey data) and several independent land-use variables. For instance, as Wang and Krajczar (1998) describe, the trip generation expressions for the Vancouver central business district (CBD) in the TransLink model are:

$$work\ production = \frac{(0.055 \times EmpRt) + (0.032 \times EmpOth) + (0.627 \times ELF)}{1.9} + 0.00001 \qquad (1)$$

$$work\ attraction = \frac{(0.503 \times EmpRt) + (0.54 \times EmpOth)}{1.9} + 0.00001 \qquad (2)$$

Where *EmpRt* is Employment Retail

EmpOth is Employment Other (non-retail)

ELF is Employed Labor Force

Work production and *work attraction* are measured in terms of number of trips. All variables refer to quantities in the CBD.

It is reasonable to assert that work trip generation equations for the Vancouver CBD would vary greatly from the post-secondary trip generation equations for Burnaby, for instance. Thus, to satisfy sub-regional differences in land-use character as well as for different trip purposes, several regression analyses were performed by TransLink to produce specific trip generation equations. Finally, the sub-regional regression analysis, aggregated for all trip types, produces zonal production and destination trips generated.

3.2.3.2.b. Trip Distribution

The second component of the UTMS, trip distribution, attempts to predict the trip flows between the origin and destination zones. In other words, it predicts where the trips generated are likely to go (using travel cost data). To do this, there are a variety models (i.e., growth factor, intervening opportunities, and disaggregate destination choice models) but the most commonly used method is the gravity model. This model, named in reference to "an analogy between the 'spatial interaction' of trip-making and the gravitational interaction of physical bodies distributed over space", is generally represented in the following expression (Meyer and Miller, 2001).

$$T_{ij} = \frac{P_i(A_j f_{ij} k_{ij})}{\sum A_j f_{ij} k_{ij}} \tag{3}$$

Where T_{ij} is the number of trips from zone i to zone j

P_i is the total number of trips produced in zone i

A_j is the total number of trips attracted to zone j

f_{ij} is the friction factor

k_{ij} is a model parameter

Since both P_i and A_j were estimated in the previous sub-model, the primary purpose in this section is to form the various friction factor equations. Meyer and Miller (2001) describe the friction factor as:

$$f_{ij} = e^{-bc_{ij}} \tag{4}$$

Where f_{ij} is the friction factor between zones *i* and *j*

c is cost of travel or impedance between zones *i* and *j*

b is a model parameter

The cost of travel or travel impedance in the transportation model describes the cost (e.g., travel time, distance, out-of-pocket costs) based on a specified mode and trip purpose. For instance, automobile travel to post-secondary institutions include travel impedance variables such as auto distance, parking cost, income levels, and the general costs for single and high occupancy vehicles. The negative exponential form of the friction factor signifies that when cost of travel increases, the likelihood of travel progressively decreases. Travel impedance for private automobile, transit, and walking modes are combined together to form the friction factor

expression in the gravity model. For example, as Wang and Krajczar (1998) illustrate, the friction factor expression for post-secondary institutions in the TransLink model is:

$$Psf_{ij} = e^{-0.072 \times PsAuImp} + e^{-0.072 \times PsTrImp} e^{-0.072 \times PsWlkImp} \quad (5)$$

Where *PsAuImp* is the post-secondary auto impedance

PsTrImp is the post-secondary transit impedance

PsWlkImp is the post-secondary walking impedance

3.2.3.2.c. Mode Split

The third component of the UTMS, mode split, attempts to predict the proportion of all the trips between an O-D pair that will be made using either private automobile, transit, or walking. The modal split method used for the Metro Vancouver transportation model relies on various logit functions. The logit method estimates the likelihood a specific mode will be used, here as a function of its relative utility for a given trip purpose (Wang and Krajczar, 1998; Meyer and Miller, 2001).

$$P_{it} = \frac{e^{Vit}}{\sum e^{Vjt}} \quad (6)$$

Where P_{it} is the probability traveler *t*, will chose mode alternative *i* from set *j*

V_{it} is the utility traveler *t*, receives from mode alternative *i*

V_{jt} is the utility traveler *t*, receives from choosing every alternative *i* from set *j*

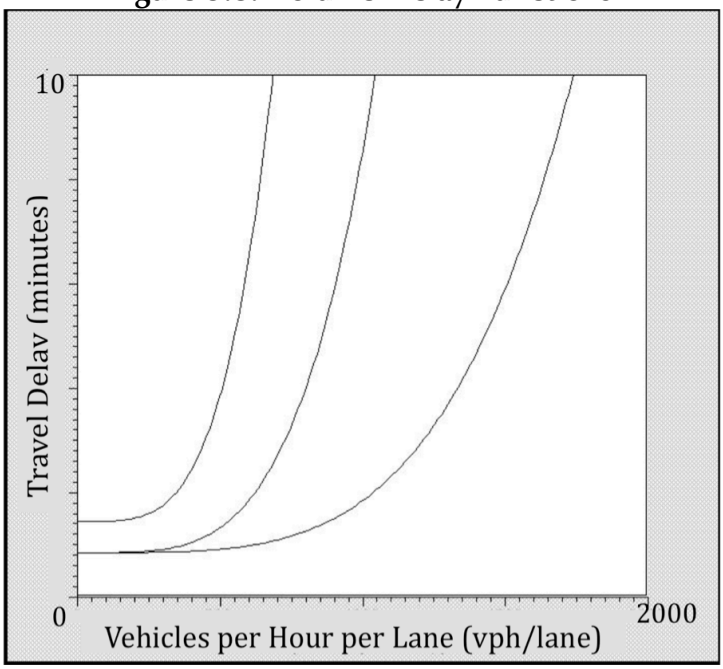
The utility functions for each mode and trip purpose in this model are a function of the travel impedances estimated in the previous sub-model. However in this model, modal split is performed in the following way. The total trips between an OD pair is multiplied by the probability travelers chose to walk. This number is then subtracted from the previous total. This process is repeated for transit probability, until the final total of trips are solely for private auto. Here the total number of trips using a private vehicle is further separated into single occupancy vehicles (SOV), two-person high occupancy vehicles (2-HOV), and finally three-person high occupancy vehicles (3-HOV).

3.2.3.2.d. Trip Assignment

The final component of the UTMS, trip assignment, assigns the trips to mode compatible routes on the transport grid (Meyer and Miller, 2001). This section by far requires the least amount

of model calculations. Several pieces of road network data are required for this sub-model. For instance, attached to each road link is information pertaining to the primary modes used on the link, link length, link type, posted speed limits, nominal capacity, operating volumes and number of lanes. Using these variables, each link is assigned a volume-delay function, which is a mathematical expression estimating the travel delay period (minutes). Such functions, seen in Figure 3.8, have an exponential form where the nominal capacity and operating volumes are generally the primary predictors for travel delay.

Figure 3.8: Volume-Delay Functions



Using an equilibrium assignment, only a few parameters are set by the modeler, such as the number of iterations or desired minimal error. An equilibrium assignment is one that assumes commuters will adjust to travel conditions. For example, suppose there were two routes from an origin zone to a destination zone. Route A is more desirable due to the relatively lower congestion levels. Consequently, 70 percent of the volume moving from the origin to destination zones is seen on Route A. As a result of this higher volume, traffic increases, making Route B a more viable option for some. Eventually both routes will reach an equilibrium, where a traveler on one route gains no benefit from switching routes. In this sub-model, it should be noted that automobile (SOV, 2-HOV, and 3-HOV) and transit assignments are performed separately.

3.2.3.3. Evaluation of Various Post-Disaster Transportation Performance Indicators

Typical post-earthquake evaluation of transportation systems takes more of a site-specific approach, often assessing single component network elements (e.g. damaged bridges). Though site-by-site assessment is structurally critical for safety purposes, this approach overlooks many transportation related concerns such as social connectivity and access to major destinations (Chang, 2003). A systems approach is what this research advocates in evaluating post-disaster transportation performance.

Measuring performance of transportation systems presents a number of methodological challenges, as well as challenges with respect to performance subjectivity. Unlike some other system evaluation indicators, which perhaps can evaluate performance in a 'cut-and-dry' manner, transportation performance measures are markedly different due to the fact that it is typically judged with a high degree of subjectivity. Transportation quality means different things to different people. For instance, a commuter travelling to work by transit may conclude that the trip was successful if a seat was available. Conversely, a person driving to work who encounters a little congestion may feel that the transportation system is performing under par. Clearly, under normal circumstances, calculating transportation quality can be difficult; attempting to evaluate transportation system performance following a large scale disaster, however, can be far more challenging due to the uncertainty in post-hazard commuter behavior (e.g. time of travel, mode choice).

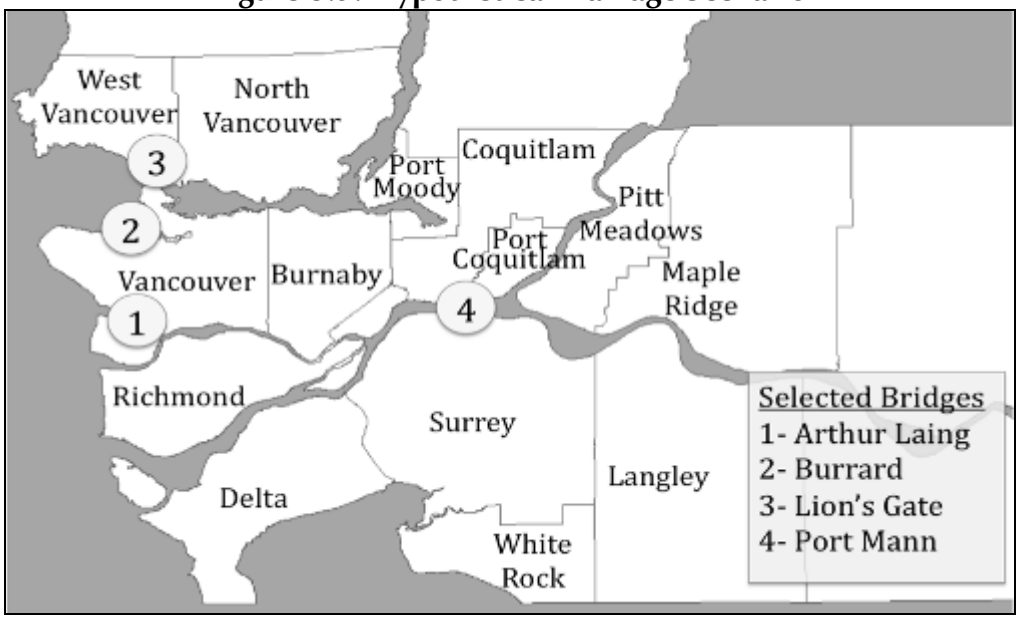
For this research, finding an appropriate transportation performance indicator (TPI) is a critical step in evaluating post-disaster transportation quality. In this section, both the strengths and weaknesses of a range of potential TPIs will be discussed to finally determine which indicator is most appropriate for this type of analysis. Ultimately, this section will suggest recommendations for the most appropriate performance measures. To do that decisions must be made regarding (1) mode type, (2) geographic scale of analysis, and (3) TPI class (relative accessibility, percent change in travel time, and equivalent monetary travel cost).

First, with respect to mode type, this thesis offers an opportunity to evaluate post-disaster transportation performance for various travel modes. For instance, we can evaluate transportation performance for a single mode (e.g. SOV) or we can evaluate performance for multiple modes (e.g. SOV, HOV, and transit). One appealing aspect of using a multiple-mode TPI is that the model will be able to account for changes commuters might make with respect to mode choice. It would appear that this approach is novel as previous examinations of post-earthquake transportation performance focus on single-mode modeling. Second, various TPIs can be evaluated at different geographic scales. For instance, performance can be measured for zones, areas of interest, or the

entire region. At the zonal level, transportation performance can be disaggregated to see which areas would experience the greatest transportation disruption. A zonal level of analysis is of particular interest for this research since the primary questions ask how both land-use characteristics and configuration, now and in the future, influence transportation performance. Transportation performance calculated for areas of interest may be of interest to certain municipalities. At the regional level, transportation performance at the zone level is distilled to a single value representative of the entire region. Though a single value representation of transportation performance is perhaps less relevant for answering this research's main questions regarding land-use, it can be useful for potential research prospects (e.g. FORM analysis). Last, the various TPIs can be grouped into the following classes: (1) Relative Accessibility, (2) Percent Change in Travel Time, and (3) Equivalent Monetary Travel Cost.

For the remainder of this section, each of these classes, geographic scales, and mode types will be discussed and compared to identify each indicator's strengths and weakness. To evaluate the suggested transportation performance indicators, a standard earthquake scenario will be used. More specifically, under this scenario the bridges considered 'damaged' or 'non-functional' will include the Lion's Gate, Arthur Laing, Burrard, and Port Mann Bridges, as seen in Figure 3.9. It should be noted that this damage scenario is entirely hypothetical. It is not based on realistic hazard or damage probabilities. Given that an ideal TPI should represent region-wide conditions, these four bridges located across the region were chosen.

Figure 3.9: Hypothetical Damage Scenario



In sum, based on the specific research questions being examined, by rank an indicator would:

1. be represented at the zone level
2. be represented at the single-value regional level
3. be easily comparable across varying network scenarios
4. contain minimal subjectivity
5. require a minimal model run time, and
6. be easily comprehensible

In every instance the indicators described will represent a comparison between pre- and post-earthquake travel time. Though many system performance indicators often utilize travel distance, as Chang (2003) discusses, travel time might be more appropriate especially in capturing detouring and queuing effects from a hazard. Furthermore, travel distance is likely not the most appropriate measure since commuters typically experience travel through time rather than distance (i.e. 'I'll be there in 10 minutes' or 'it's a 15 minute wait for the bus'). Therefore, for the purpose of this research, each evaluated TPI will be a function of travel time. Furthermore, travel time data between origin-destination pairs still need to be normalized by travel demand. This is a critical step, since simply using the un-normalized travel time data would skew the results. For instance, if the commuting time from Delta to downtown Vancouver is high but no commuters choose to travel between these areas, the high travel time should not distort the performance indicator. By normalizing the travel time data by demand, the resulting output becomes vehicle hours traveled (VHT).

3.2.3.3.a. Relative Accessibility Ratio

Chang and Nojima (2001) had proposed a post-earthquake system performance measure based on concepts of accessibility. Here accessibility is defined as the "ease with which land-use activities…can be reached from a location by using a transportation system", here measured through travel time (Chang and Nojima, 2001; Chang, 2003). Relative accessibility (also referred to as simply accessibility) (A_s) in the varied forms proposed here, is generally the ratio of the vehicle hours traveled on a damaged network to the vehicle hours traveled on an undamaged network (Equation 7). This would produce values between 0 and 1 which signify that the transportation system is non-functional and fully-functional, respectively.

$$A_s = \frac{\sum_{r \neq s} d_{rs,t}^{-\gamma}}{\sum_{r \neq s} (d_{rs}^{*})^{-\gamma}} \tag{7}$$

Where A_s is relative accessibility for destination zone s

d_{rs} is the VHT (*t*) on a damaged network between zone r and zone s

d^*_{rs} is the VHT (*t*) on an undamaged network between zone r and zone s

γ is a distance-decay parameter (=1)

Using this ratio, accessibility at the zonal level (summed to destinations) can be derived. To calculate accessibility for areas of interest, and for the entire region, a weighted mean is calculated using travel demand to destinations. For instance, consider the example in Table 3.4. In this example, the weighted average of accessibility is 0.78.

Table 3.4: Example of Calculating Accessibility for 'Areas of Interest' and the 'Region'

Zone	Zonal Accessibility (A)	Travel Demand to Zone (B)	Percent of Travel Demand to Zones (C=B/5932)	Weighted Accessibility (A*C)
1	0.9	234	3.94 %	0.04
2	0.75	4256	71.75 %	0.54
3	0.8	932	15.71 %	0.13
4	0.9	510	8.60 %	0.08
Total		5932	100.00 %	**0.78**

Applying the standardized damage outcome described earlier, various accessibility values were derived. At the zonal level, accessibility was far more diminished in parts of Surrey, downtown Vancouver, and North Vancouver as seen in Figure 3.10. As seen in Table 3.5, for the entire Metro Vancouver area, the Regional Accessibility was **0.90**. Accessibility to an area of interest (downtown Vancouver) was **0.79**. Understandably, by being more selective in which geographic scale to choose, results vary. By including 'areas of interest' Accessibility is more sensitive to the damage scenario.

Figure 3.10: Zonal Accessibility

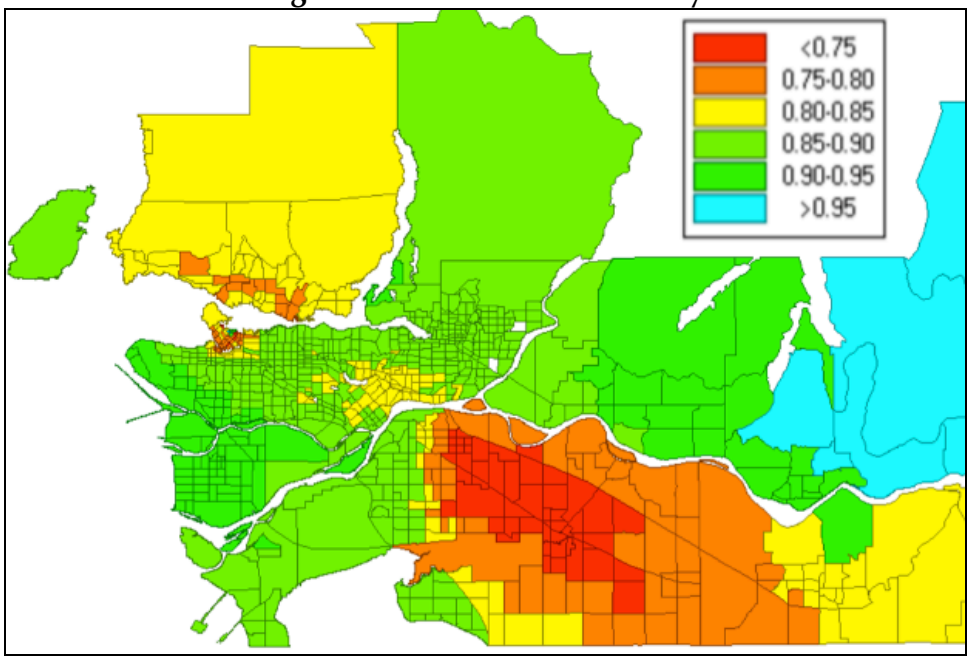


Table 3.5: Summary of Accessibility Results

Geographic Scale of Accessibility	Accessibility Value
Regional	0.90
Area of Interest (downtown Vancouver)	0.79

3.2.3.3.b. Percent Change in Travel Time

In a similar manner to Accessibility, percent change in vehicle hours traveled, as described in Equation 8, can also be measured (1) at the zonal level (summed to destinations) as seen in Figure 3.11, (2) to areas of interest, and (3) for the entire region. Again, the latter two measurements are calculated using a weighted mean, derived in a similar manner as described in the previous section. Using this measure, there again appears to be a greater travel disruption in downtown Vancouver, North Vancouver, and Surrey as seen in Figure 3.11. Regionally, Metro Vancouver saw a **10.5%** increase in travel time. Finally, for areas of interest, such as downtown Vancouver, there was a **20%** increase in VHT. As seen in Table 3.6, again it would appear that by focusing on specific areas of interest, performance or % change in travel time is more exaggerated.

$$\%Change = \left(\frac{\left[\sum_{r \neq s} PSTeqTT_{rs} - \sum_{r \neq s} PREeqTT_{rs} \right]}{\sum_{r \neq s} PREeqTT_{rs}} \right) \times 100 \quad (8)$$

Where $PSTeqTT_{rs}$ is post-earthquake VHT between zone r and zone s

$PREeqTT_{rs}$ is pre-earthquake VHT between zone r and zone s

Figure 3.11: Percent Travel Time Increase

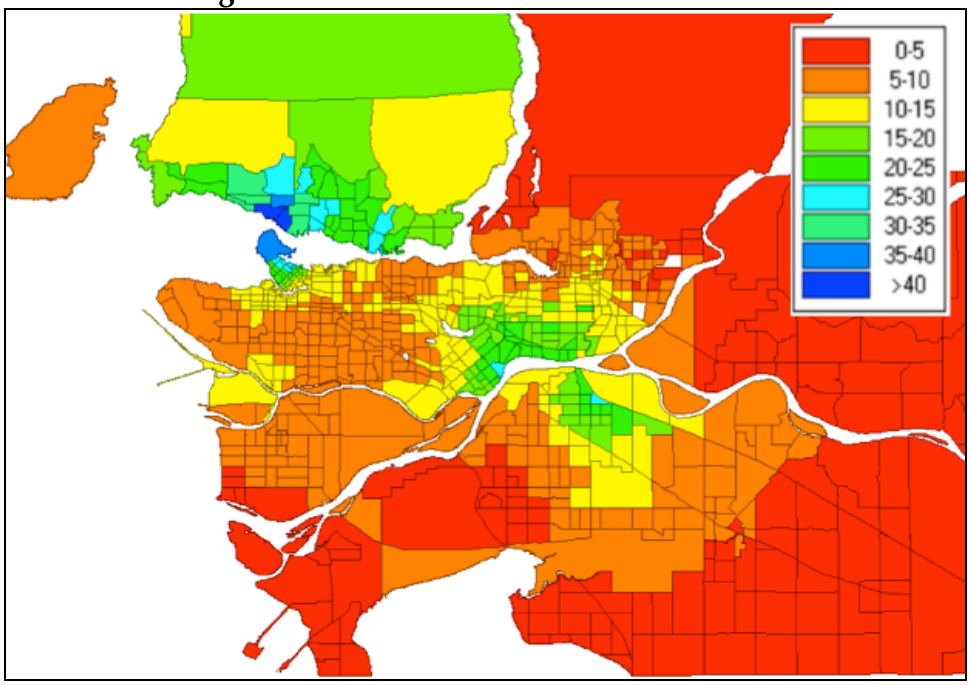


Table 3.6: Summary of Percent Travel Time Change Results

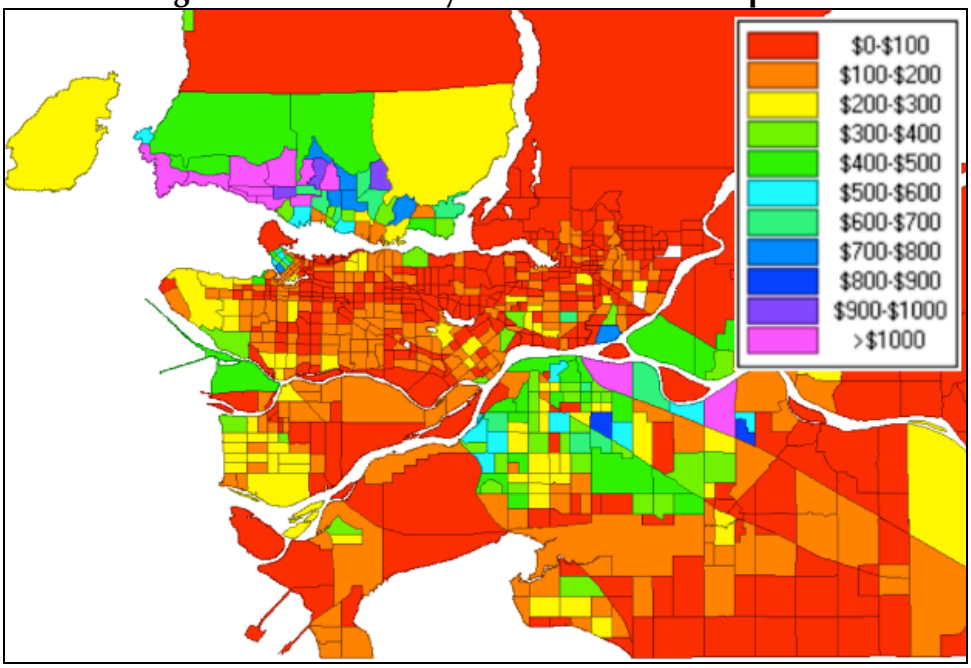
Geographic Scale of Accessibility	Percent Change (%)
Regional	10.5
Area of Interest (downtown Vancouver)	20

3.2.3.3.c. Monetary Cost of Travel

Often one of the largest justifications of a major transportation project, such as the construction of a bridge, is the travel time savings. When decision-makers weigh the costs and benefits of such a project, they distill costs and benefits to a common denominator; typically, a dollar amount. Construction and similar costs are easily computable; however, the benefits of

travel time savings are far more complicated to calculate. Generally in this type of cost-benefit analysis, total travel time summed to destinations is converted to a dollar amount using average zonal wage, which is a proxy for 'value of time' (Litman, 2009). It may be a crude estimation, but the average annual wage per zone is simply multiplied by the VHT to each zone. As Todd Litman (2009) described, based on the level-of-service (LOS) we can determine the value of time, or how much travel time is worth to a commuter. Level-of-Service is a ranking system for measuring transportation quality based on speed, flow, and density (Litman, 2009). If a transportation system is experiencing a poor LOS (e.g. LOS F), then commuters would suffer greater economic hardship than if the system were in excellent condition (e.g. LOS A). In sum, the regional cost following the damage scenario would be **$143,961** for every peak hour travelled. At the zonal level results appear to be more varied, though North Vancouver, Surrey, and downtown Vancouver again experience greater cost (Figure 3.12).

Figure 3.12: Monetary Cost of Travel Disruption



3.2.3.3.d. Summary and Evaluation of Transportation Performance Indicators

To summarize, an ideal performance indicator would generally be easily comprehensible, computable, comparable, and contain a minimal amount of subjectivity. Furthermore, it should be possible for the indicator to be represented as a single-value and for each zone. There are several TPI options available that cover different classes, geographic scales, and mode-sharing options. Summarized in Table 3.7 are the TPIs evaluated against several objectives (ranked in importance).

Working our way across the alternatives, we first encounter the decision to either use single- or multi-mode sharing. In every instance, we have the option of evaluating transportation performance for one or for several modes. Original thoughts were to perform a simple 'trip assignment' for only the SOV (single-occupant vehicle) mode as this is the dominant mode used by commuters. However, we have the option of performing a 'model equilibrium' which would tell us the travel time apportioned among all three major modes (SOV, HOV, and Transit). Though a multi-modal split may provide more realistic travel behavior outputs following a bridge closure, performing model equilibrium can take several hours (as seen in objective 5: model run-time), versus a trip assignment which takes several minutes.

Choosing among the various geographic scales, and considering that this research is concerned with the connection between regional form and transportation disruption, a more appropriate indicator would likely contain some influence of land-use. For the purposes of this research, a zonal performance indicator will likely be more appropriate for the research questions being assessed. The 'area of interest' TPI is also an interesting measure of transportation performance but there is a high degree of subjectivity associated with this indicator. Furthermore, by limiting the areas considered, we limit the amount of data and reduce any analysis in comparing regional form and transportation disruption. For these reasons, this TPI is not appropriate. Ideally, the zone level of analysis would be best since it can show which areas would be most affected, which land-use characteristics contribute to heightened risk, and how the land-use configuration affects risk. However, a single-value regional TPI could be necessary for future research. Therefore, using a performance at the zone level which can also be converted to a single value would be ideal for this research.

Among the various TPI classes monetary cost appears to be the most graspable. Communicating what the dollar cost of transportation disruption to the public, a decision-maker, or a politician is much more palpable and discernible than other indicators. Though this indicator is valuable for its comprehensibility, some of the assumptions used to construct this TPI are coarse and can draw criticism. Though 'percent change' is used in many types of analysis largely for its comprehensibility, this measure is unbounded, which makes capturing diminished performance and comparing across different scenarios difficult. Despite this, it can be represented at the zone and regional levels. Accessibility is an appealing TPI also because it can be represented at the zone level and be reduced to a single-value for the entire region. Furthermore, unlike percent change, which does not provide an indication of diminished performance, having a scale of 0 to 1 makes comparability less subjective.

In sum, it is my recommendation that for the purposes of this research, an Accessibility measure at the zone-level, from which a regional accessibility can be derived, is most appropriate. This measure allows for analysis of how regional form contributes to transportation risk, and comparisons across various land-use and damage scenarios. Furthermore, though a multiple-mode TPI is appealing as it is able to capture mode-sharing changes following a disaster, the high model run-time is the main reason why the single-mode option was chosen.

Table 3.7: Objectives-Alternatives Consequence Table

Alternative / Objective			Zonal Rep. (1)	Regional Rep. (2)	Comparability (3)	Subjectivity (4)	Model Run-Time (5)	Comprehensibility (6)
Mode	*Class*	*Geo. Scale*						
Single Mode	Accessibility	Destination	Yes	No	High	Low	Low	Medium-High
		Region	No	Yes	High	Low	Low	Medium-High
		Area of Interest	Yes	No	High	High	Low	Medium-High
	% Change	Destination	Yes	No	Medium	Low	Low	Medium-High
		Region	No	Yes	Medium	Low	Low	Medium-High
		Area of Interest	Yes	No	Medium	High	Low	Medium-High
	$	Destination	Yes	No	Medium	Medium	Low	High
		Region	No	Yes	Medium	Medium	Low	High
Multi-Mode	Accessibility	Destination	Yes	No	High	Low	High	Medium-High
		Region	No	Yes	High	Low	High	Medium-High
		Area of Interest	Yes	No	High	High	High	Medium-High
	% Change	Destination	Yes	No	Medium	Low	High	Medium-High
		Region	No	Yes	Medium	Low	High	Medium-High
		Area of Interest	Yes	No	Medium	High	High	Medium-High
	$	Destination	Yes	No	Medium	Medium	High	High
		Region	No	Yes	Medium	Medium	High	High

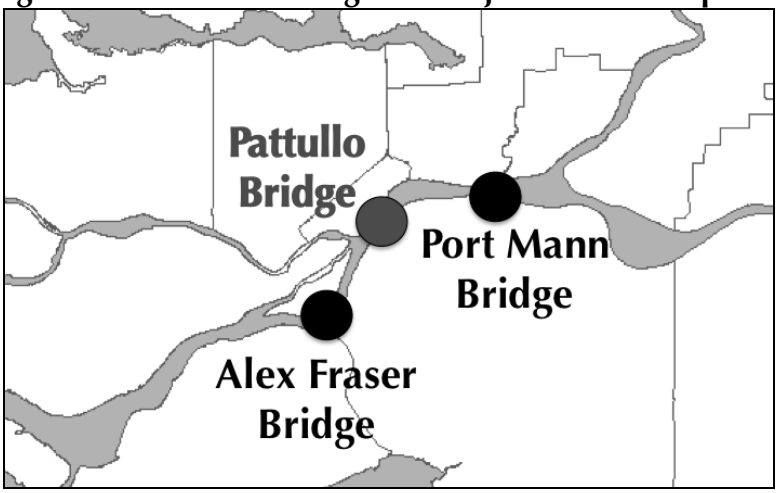
3.2.3.4. Model Verification: Pattullo Bridge Closure

On Sunday January 18th, 2009 a fire burned a section of the Pattullo Bridge's wood trestle. Immediately following the bridge's closure, travel disruption was seen across parts of the Lower Mainland. The Pattullo Bridge, one of Metro Vancouver's busiest bridges, connects Surrey and New Westminster across the Fraser River. Initial estimates suggested that the bridge would be closed for four to six weeks, but fortunately "engineers were able to modify a temporary bridge left over from the Canada Line construction" and replace the damaged section (CBC, 2009[4]). The bridge was reopened a week later, but during its closure, commuters were forced to alter their travel route.

Though the closure had caused significant travel disruption, it does provide this research with a valuable opportunity for model verification. The event is particularly interesting since it essentially replicates our methodology: remove a bridge from our transportation model and observe how transportation flows respond. To test whether actual versus forecasted travel behavior is comparable, we obtained travel data from the Ministry of Transportation (BC Ministry of Transportation, 2009). Travel data were available for the weeks before, during, and after the bridge closure. Though data were available from Monday through Friday, when observing a typical weekday it is generally good practice to use information from the middle of the week (i.e. Tuesday, Wednesday, and Thursday). The reasoning behind why Mondays and Fridays were excluded in this type of analysis is because they tend to retain some of the residual effects of the weekend and distort the typical weekday (Levine and Wachs, 1998). The travel data were from permanent count stations located at (1) Port Mann Bridge, (2) Alex Fraser Bridge, (3) Oak Street Bridge, and (4) Deas Tunnel. Traffic volume data obtained from the Port Mann and Alex Fraser Bridges are of particular interest, as these bridges are situated on either side of the Pattullo Bridge and are relatively convenient alternatives to get across the Fraser River (Figure 3.13). It is our assumption that due to the loss of the Pattullo Bridge, these two bridges are expected to see increases in AM peak volumes.

[4] http://www.cbc.ca/canada/british-columbia/story/2009/01/26/bc-pattullo-bridge-reopens.html

Figure 3.13: Pattullo Bridge and Adjacent Travel Options



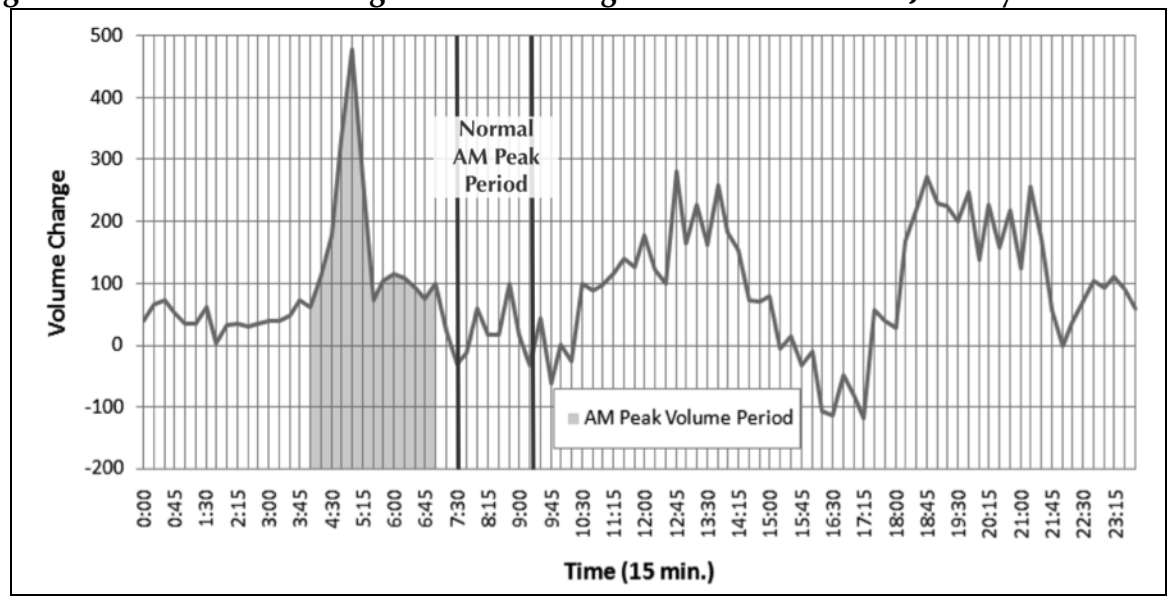
After removing the Pattullo Bridge from the Vancouver Transportation Model, forecasted traffic volumes on the Port Mann and Alex Fraser Bridges increased by 33% and 31% respectively (Table 3.8) during a typical weekday morning rush-hour.

Table 3.8: Vancouver Transportation Model: Bridge Volume Change

	Pre-Closure Volume	Post-Closure Volume	Percent Change
Port Mann Bridge	6217	8286	**33.28%**
Alex Fraser Bridge	5556	7305	**31.48%**

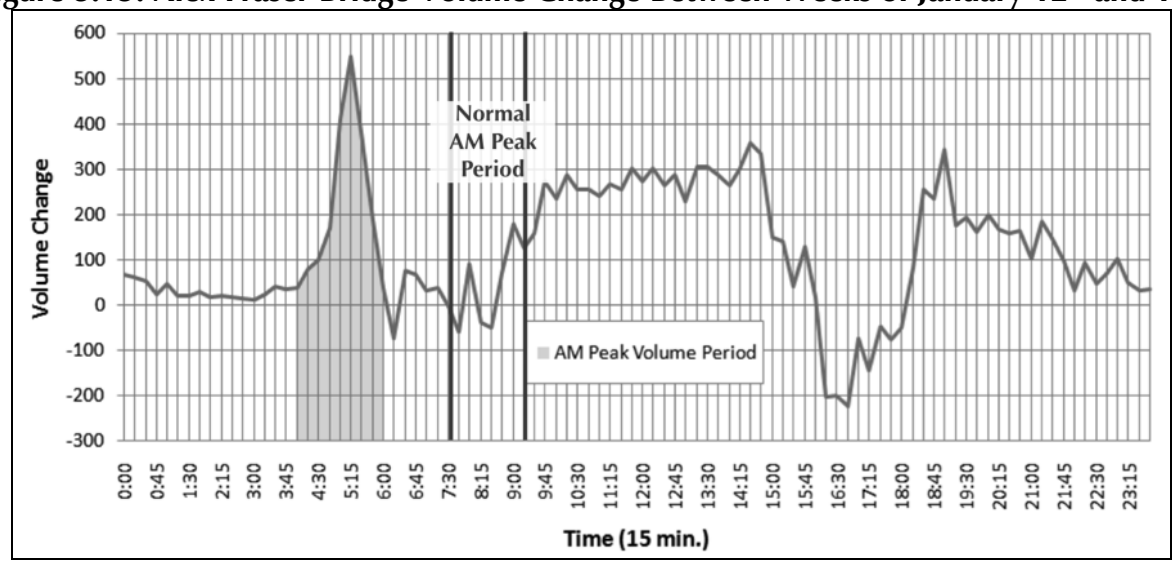
Upon comparison of these values with the empirical data provided by the Ministry of Transportation, what was puzzling was there was a very minimal change in volume during the morning rush-hour (i.e. an hour between 7:30 and 9:30 am as the Vancouver Transportation Model defines it) as seen in Figure 3.14 and Figure 3.15. These figures plot the change in the average 'mid-week' volume in the weeks before and after the closure. After further examination of these figures, it is evident that both bridges experienced dramatic spikes in volume prior to the morning rush-hour, clearly attributable to the Pattullo Bridge closure. For the Port Mann Bridge this increase in traffic volume occurred roughly between 4 and 7 am. The average hourly percent increase in volume during this time was 32.37%. For the Alex Fraser Bridge, this rise in volume was seen between 4 and 6 am. During this period the average hourly percent increase in volume was 35.76%. So it would appear that though the predicted versus actual volumes do not match up with respect to time, it does seem to appear that the magnitude of change is consistent.

Figure 3.14: Port Mann Bridge Volume Change Between Weeks of January 12th and 19th



Source: British Columbia Ministry of Transportation, 2009

Figure 3.15: Alex Fraser Bridge Volume Change Between Weeks of January 12th and 19th



Source: British Columbia Ministry of Transportation, 2009

3.2.4. Sampling Analysis

Overall, the hazard model generates sub-crustal earthquake realizations with hypocenter locations located in Metro Vancouver. Using an attenuation algorithm developed by Atkinson (2005), the spectral acceleration at 10 bridge sites across Metro Vancouver is determined. Each of the 10 bridges have an associated bridge structural model, which uses this intensity measure to determine the degree of damage each bridge will likely experience. The output of the structural model is a bridge functionality ranging from 0 to 1. However, though bridge functionality is a

continuous value, in this research each bridge's functionality it converted to a binary value (i.e. 0 or 1). Using a rounding threshold of 0.98, bridge functionality values which are below and above 0.98 are either rounded down or up to 0 and 1, respectively. Considering that there are 10 bridges under study, each of which can be either opened or closed, there are 1024 possible damage outcomes. When the sampling process commences, the output of the bridge structural model will be a series of ten binary numbers which represent the ten bridge's functionality; a 'bridge damage outcome'. For instance, the structural model may generate a damage outcome such as '0010000001'. What this outcome indicates is that Bridge 3 and Bridge 10 experience full-functionality, whereas all other bridges will be closed. All 1024 possible damage outcomes are stored in a lookup table with an associated damage outcome ID number, as seen in Table 3.9. In the sampling process, once the 10-digit damage outcome is produced by the structural model, a tool in Rt referred to as the 'Transportation Bridge Failure Reader' finds the 10-digit damage outcome from the lookup table and plots its associated ID number in a histogram. Once all 10,000 samples are complete, a plot of the most frequent damage outcomes is produced.

Table 3.9: Look-Up Table of Damage Outcomes

Damage Outcome ID	Bridge Damage Outcome
1	0000000000
2	0000000001
3	0000000010
4	0000000011
5	0000000100
6	0000000101
...	
1018	1111111001
1019	1111111010
1020	1111111011
1021	1111111100
1022	1111111101
1023	1111111110
1024	1111111111

3.2.5. Land-Use Change

An examination of the changes to the regional form will begin broadly and then narrow its focus in Chapter 4 (Research Findings), by first looking at the land-use changes for the entire region and then subsequent changes at the link level. This section summarizes land-use and travel demand changes between TransLink's 2004 regional transportation model and its 2021 (projected) model. The two models are identical in terms of the transportation network (e.g., number of bridges).

Between 2004 and 2021, Metro Vancouver experiences noticeable change to its regional form. In particular, the total population and total employment change between 2004 and 2021 are visually represented in Figure 3.16 and Figure 3.17 respectively. One will notice that overall, there appears to be a general increase in both total population and total employment. However areas mostly in the North Shore see decreases in total population and employment. Conversely, there appears to be increases in total population and employment south of the Fraser River. These patterns are generally reflected in changes in SOV demand between 2004 and 2021. Among single occupancy vehicle users, total AM peak hour commutes rises from 259,948 to 316,521, a 21% increase. As illustrated by Figure 3.18, changes to the regional form cause an overall increase in demand as represented in blue. In particularly, southeast Richmond and much of Surrey see significant increases in demand over 17 years. However, though much of the region sees an increase in demand, many areas including North and West Vancouver, as well as parts of downtown and areas in Coquitlam see reductions in demand between 2004 and 2021.

Figure 3.16: Change in Total Population between 2004 and 2021

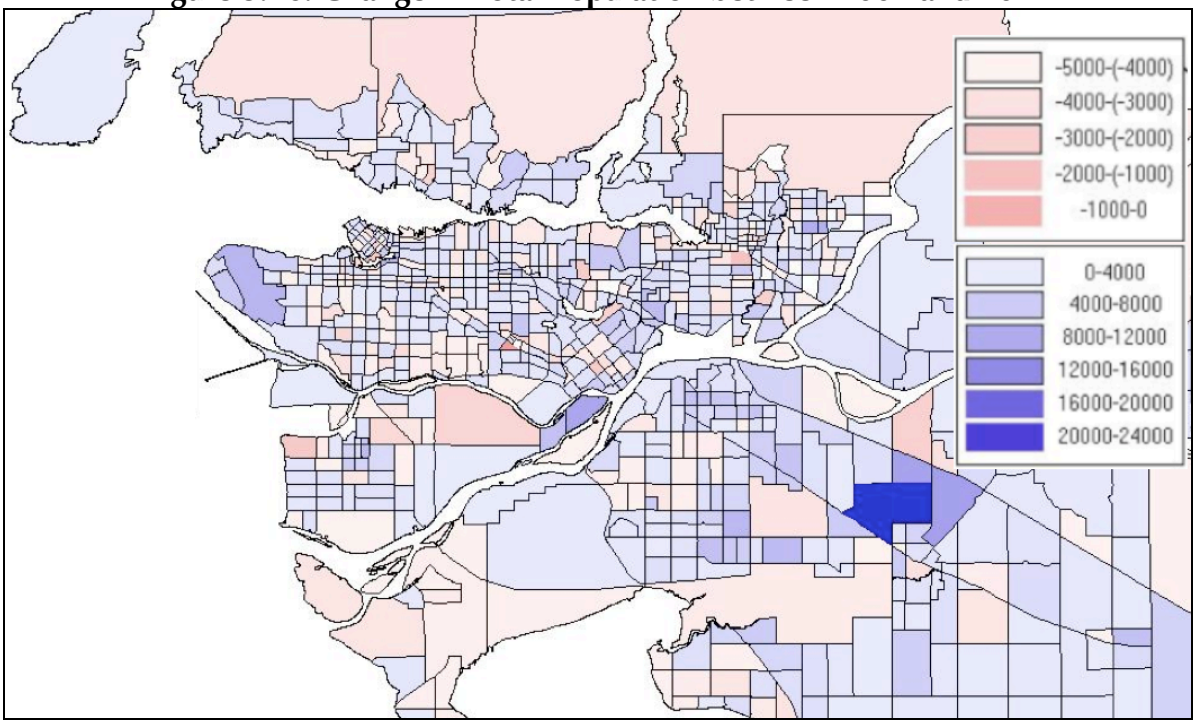


Figure 3.17: Change in Total Employment between 2004 and 2021

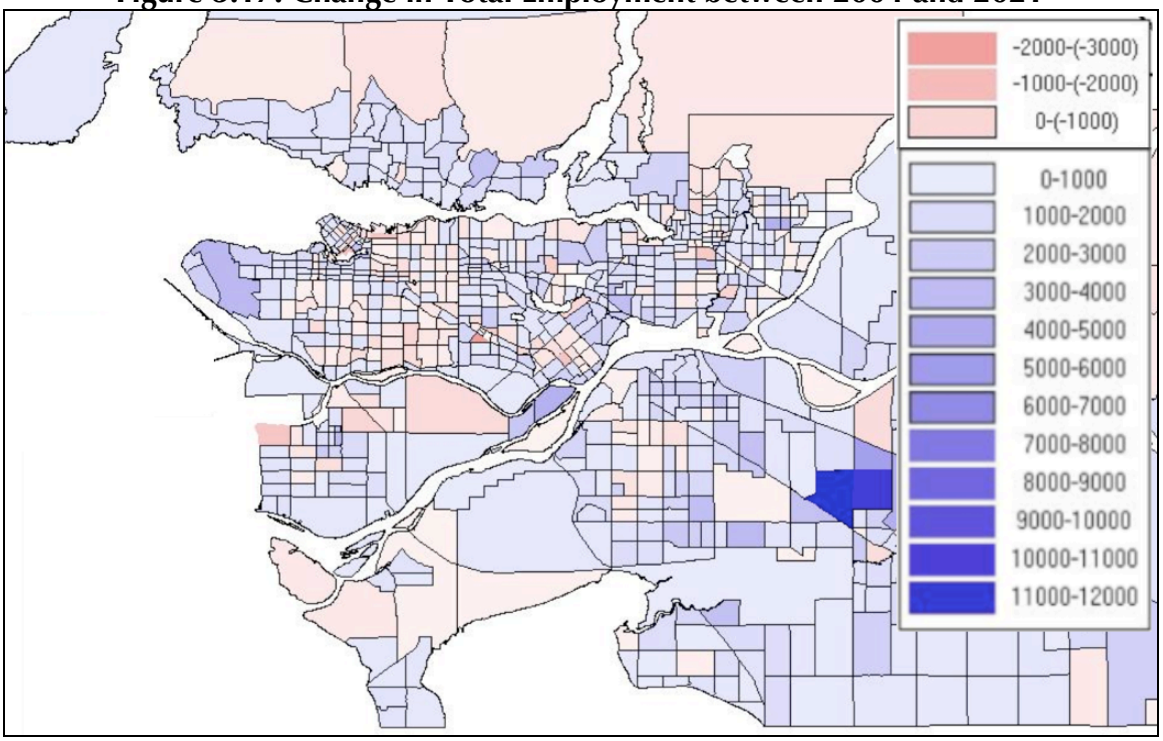
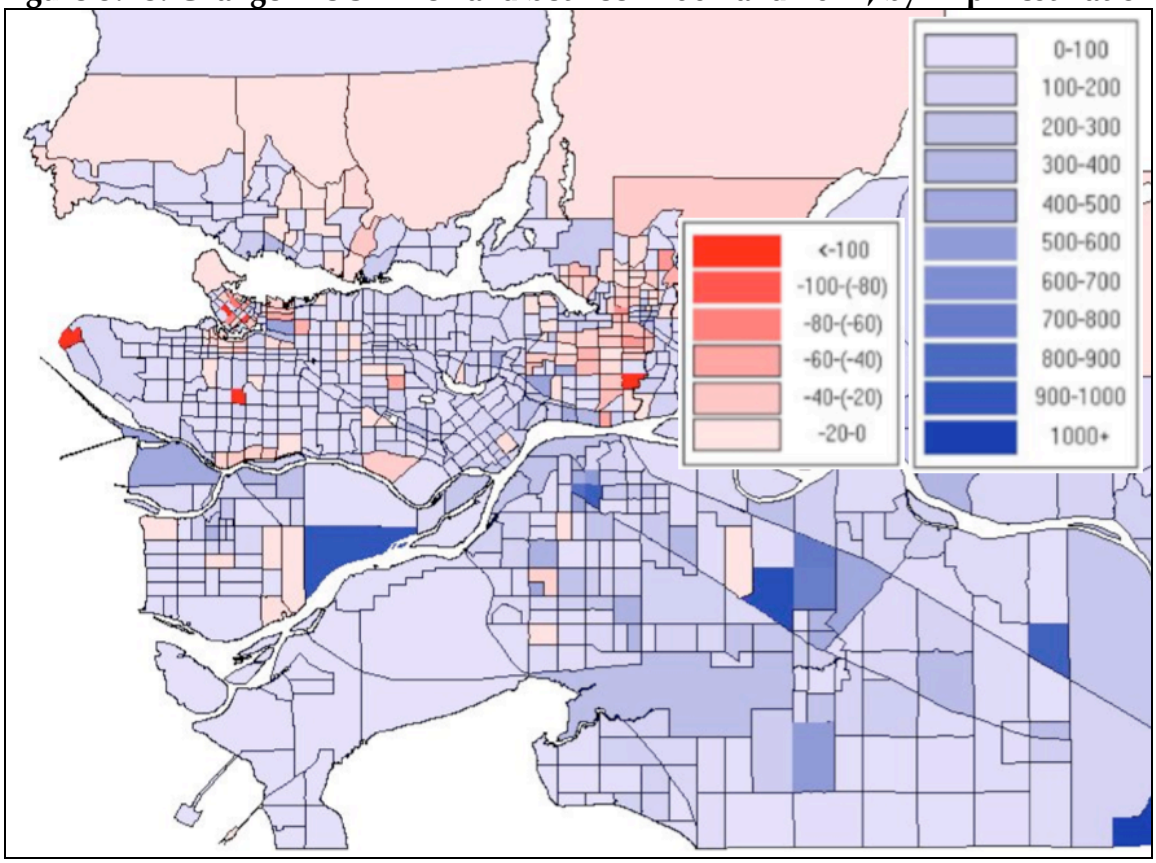


Figure 3.18: Change in SOV Demand between 2004 and 2021, by Trip Destination



It should be noted that the closure of a bridge forces its users to find an alternate route. The extent of spillover these commuters place onto the surrounding network will dictate the degree of post-disaster transportation performance. Thus, it is critical to understand where these bridge users travel to, and how they contribute to greater transportation disruption. In the next chapter, we will identify which bridges are likely to experience damage. In identifying vulnerable bridges, we will also characterize the bridge users who will place strain on surrounding road networks after an earthquake.

3.2.6. Concluding Remarks

In summary, this section has presented a methodological framework that consists of a hazard, bridge structural, and transportation model. The approach utilizes Rt's sampling methods tool to generate 10,000 earthquake realizations in Metro Vancouver. The output of the hazard model is an intensity measure (i.e. spectral acceleration) that is used by the bridge structural model. The bridge structural model was developed using previously constructed models developed by FEMA (2003). Overall, the model generates likely damage outcomes that will be used by the transportation model. The transportation model and its data were provided by TransLink, and it would appear that modeling post-earthquake travel conditions are accurate after a model verification was performed. Furthermore, after evaluating various transportation performance indicators, it appears that the most appropriate is Accessibility.

Chapter 4. Research Findings

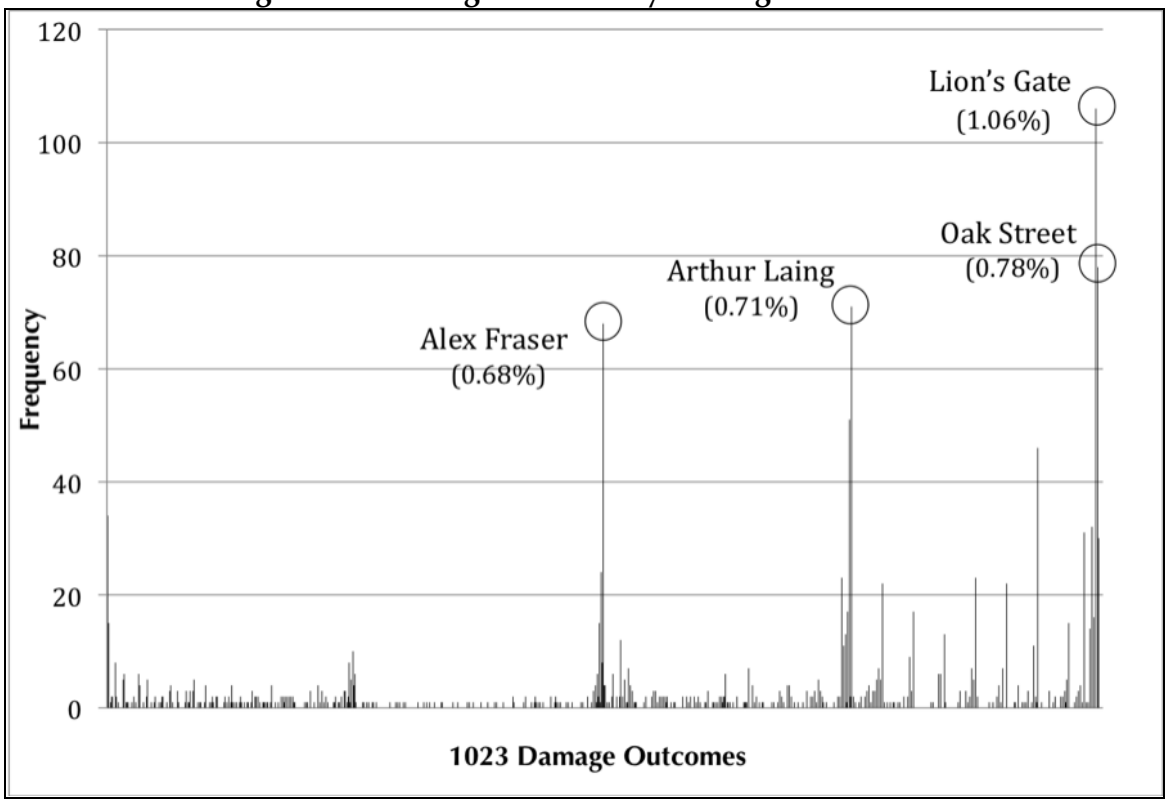
This chapter presents the principle results from this research. Specifically, it will describe the results of the sampling analysis that was performed, identify the most frequent damage outcomes, and describe the effects diminished transportation performance will have for the region's commuters. Given that this research is concerned with studying the effects 'regional form' plays in how post-disaster transportation performance changes over time, an analysis of changing land-use configurations will also be conducted.

After conducting a fairly basic sampling analysis, which in total generated 10,000 earthquake scenarios (as described in Section 3.2.4, "Sampling Analysis"), results generated by simplified hazard and structural models show that for the most part, the Metro Vancouver transportation system, at a structural level, performs reasonably well under hazardous conditions. Bearing in mind that following an earthquake all ten bridges can either be open or closed, there are a total of 1024 possible outcomes; one of which sees no damage. Overall in the sample of earthquakes considered, results show there is an 85% probability that none of the ten bridges will experience any damage. Of all the remaining 1023 potential outcomes ("damage outcomes" in Figure 4.1), damage appears to predominantly affect a single bridge in isolation. In other words, there are few instances which see multiple bridges failing at once. As Figure 4.1 illustrates, the most frequent damage outcomes will see the closure of the Lion's Gate, Oak Street, Arthur Laing, and Alex Fraser Bridge with probabilities of occurrence of 1.06, 0.78, 0.71, and 0.68 percent, respectively. Though other damage outcomes are statistically possible, these four appear to be the most likely and thus will consume the bulk of analysis for the remainder of this section.

It should be noted, however, that multiple-bridge closure outcomes do occur. In general, the most frequent multiple bridge closure outcomes appear to be some combination of these four bridges. For instance, there is a 0.51% probability that both the Arthur Laing and Oak Street Bridges will be closed. However, again due to their relatively lower probabilities they will not be discussed. Instead, this section will focus on deconstructing the four most likely outcomes.

These results show that the probability of serious damage to Metro Vancouver's transportation system is low. Despite this, these four potential damage scenarios can have serious social and economic implications, given that each bridge facilitates the movement of thousands of commuters everyday. It should be noted that to help illustrate certain patterns in the results, the order in which these likely damage outcomes will be discussed are as follows: (1) Lion's Gate, (2) Alex Fraser, (3) Arthur Laing, (4) and Oak Street Bridge damage outcomes.

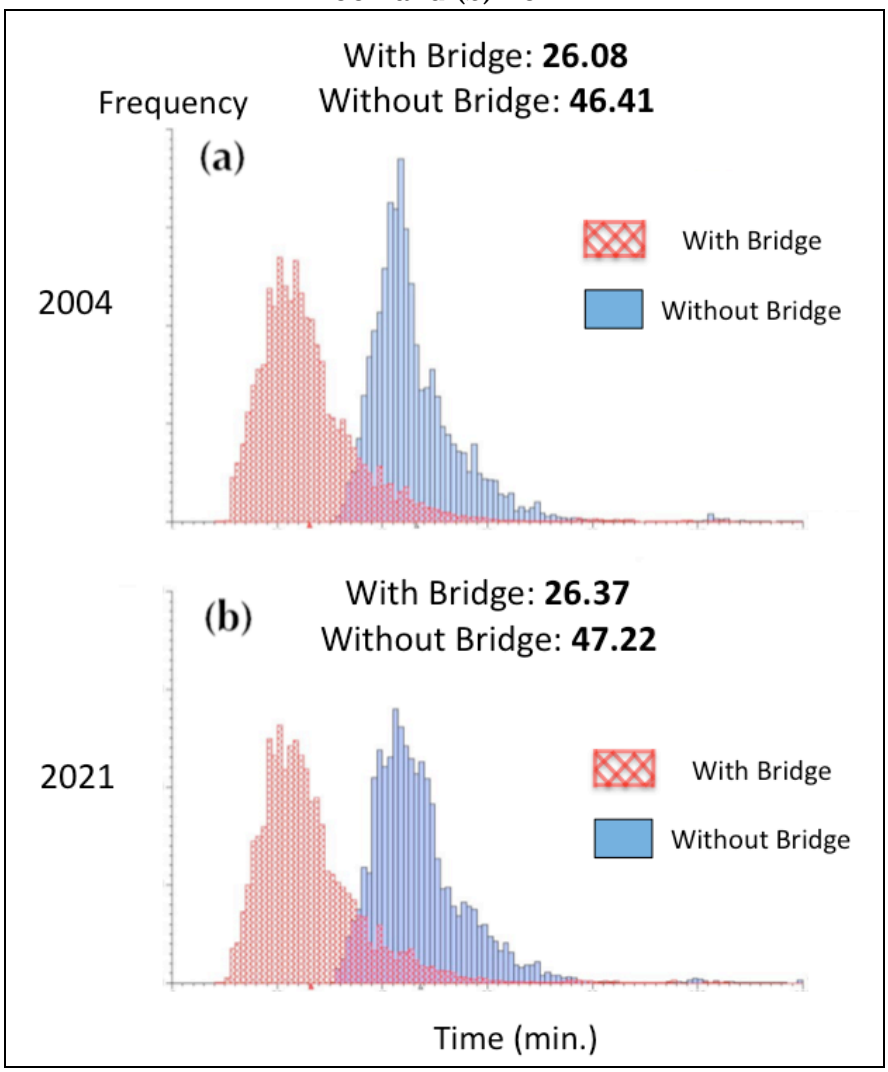
Figure 4.1: Histogram of Likely Damage Outcomes



4.1. Lion's Gate Bridge Damage Outcome

With its closure, Lion's Gate Bridge users will experience significant travel disruption. As seen in Figure 4.2 (a) and (b) average travel times for bridge users before and after the closure are 26.1 and 46.4 minutes in 2004 and are 26.3 and 47.2 minutes in 2021, respectively. What is interesting is that following the bridge closure, the increase in travel time for these users in 2004 and 2021 is about the same. Regardless, a twenty-minute average increase in commute times for both periods is quite significant, particularly for those traveling to downtown and parts of North and West Vancouver.

Figure 4.2: Pre- and Post-Earthquake Travel Times for Lion's Gate Bridge Users in (a) 2004 and (b) 2021

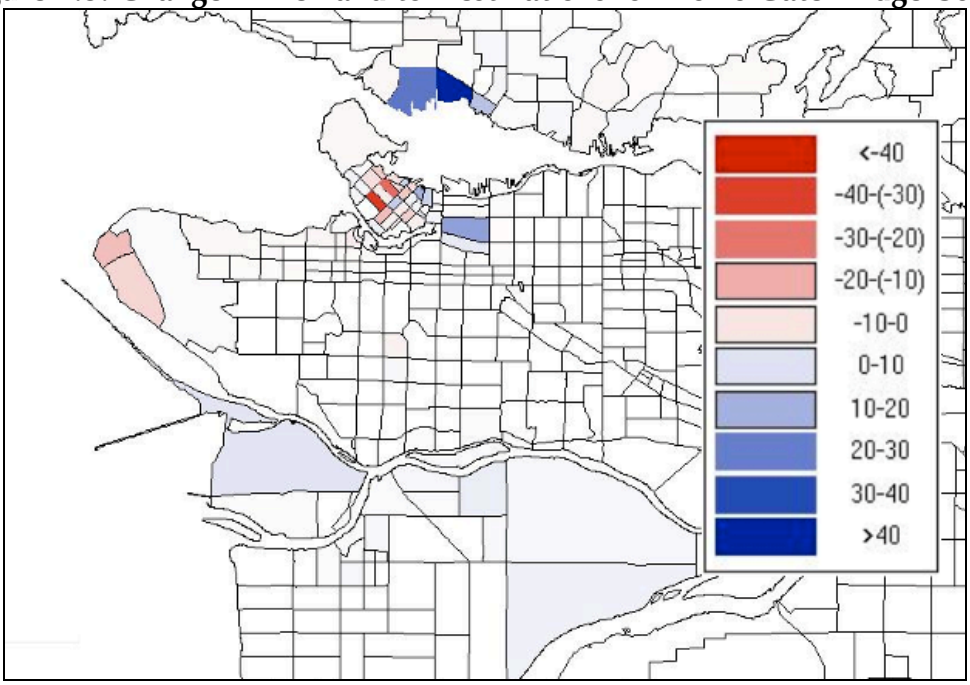


Upon examination of this figure, there appears to be no significant difference in the increase in travel time for bridge users between 2004 and 2021. This is unusual, considering that normally over a near two-decade period the travel times for bridge users should change to some degree. The source of this stagnation became evident as results showed that overall bridge usage or the total number of commutes between 2004 and 2021 were 4391 and 4402 respectively; a very modest 0.11% increase in bridge usage.

An examination of Figure 4.3 shows the change in the number of commutes to various destinations Lion's Gate Bridge users travel to between 2004 and 2021 (with no earthquake). It should be noted that this figure has a graduated colour ramp that was produced by linear interpolation. What is important regarding this figure is that, negative values are represented in red, positive values are represented in blue. The lighter and darker shades for both colours represent lower and higher values, respectively. Much of the figure is white, which indicates that

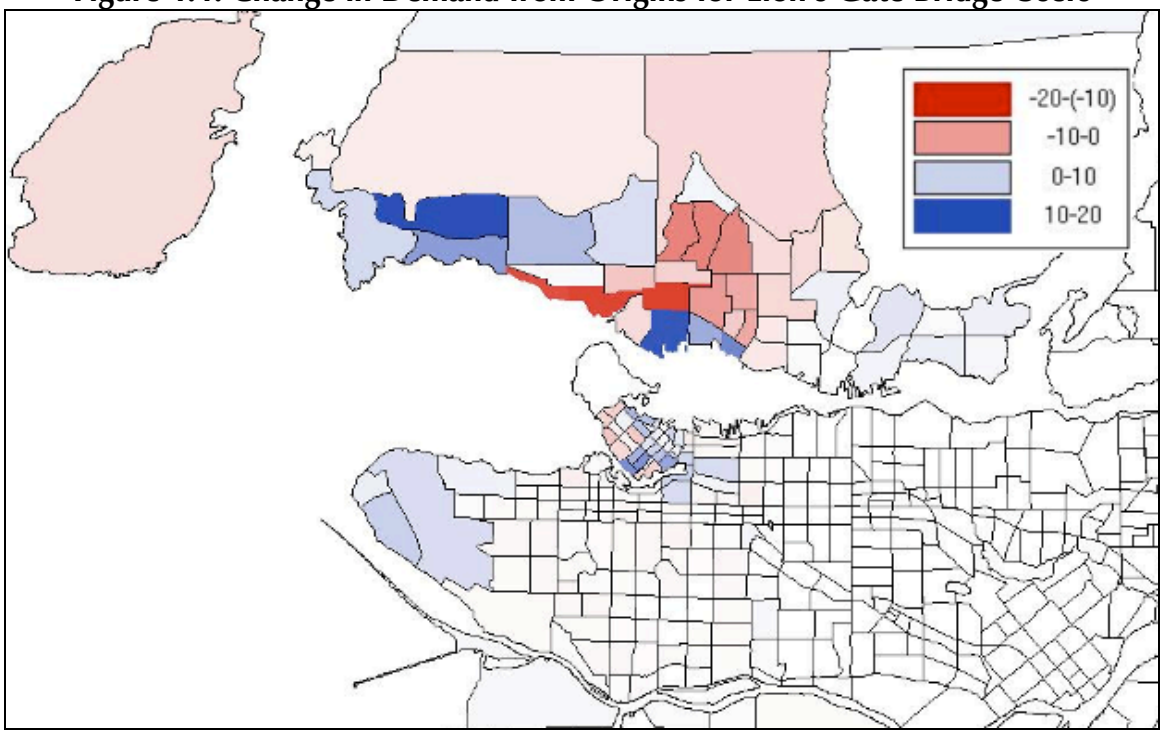
most of the region has little change in demand. However, as expected the greatest number of commutes are to destinations in close proximity to the bridge.

Figure 4.3: Change in Demand to Destinations for Lion's Gate Bridge Users



As seen in this figure, it appears that the undersized growth of bridge usage is a result of a balanced combination of both an increase and decrease in bridge demand. These opposing factors have acted to suppress one another, and they are the cause for this minimal change in bridge usage. For the most part the increases and decreases in demand to destinations are associated with increases and decreases in total employment in these zones. Also, in one case an area saw a reduction in demand despite an increase in employment. Further analysis shows that the zones from which these commuters originate see significant drops in total population (Figure 4.4). Overall, as a consequence of countering increases and decreases in regional employment and population concentrations, bridge usage has remained relatively stagnant.

Figure 4.4: Change in Demand from Origins for Lion's Gate Bridge Users



When observing the effects of this closure at a regional level, based on the information stemming from the travel behavior of the Lion's Gate Bridge users, results are somewhat expected. The areas generating the greatest travel demand by bridge users see the most intense travel disruption, here measured as accessibility. Again, this measurement is a ratio that represents pre- and post-disaster transportation performance. As seen in Figure 4.5 and Figure 4.6, which show the regional distribution of accessibility in 2004 and 2021 respectively, all of West Vancouver, and parts of North Vancouver experience the greatest diminished transportation performance. During both periods, downtown Vancouver will see some reduced accessibility. Furthermore, municipalities directly north and south of the Fraser River including, Delta, Surrey, White Rock, Langley, Richmond, Burnaby, and Port Coquitlam also see diminished transportation performance. Figure 4.7 compares the percent change in accessibility between 2004 and 2021 following the Lion's Gate Bridge closure. Interestingly, the figure shows that much of the region sees an increase in accessibility as indicated by the blue. Conversely, North and West Vancouver, as well as parts of Vancouver see accessibility diminish. One must not conflate the two findings that though transportation disruption does increase, over time the amount of disruption is reduced.

Figure 4.5: Lion's Gate Damage Outcome 2004 Accessibility

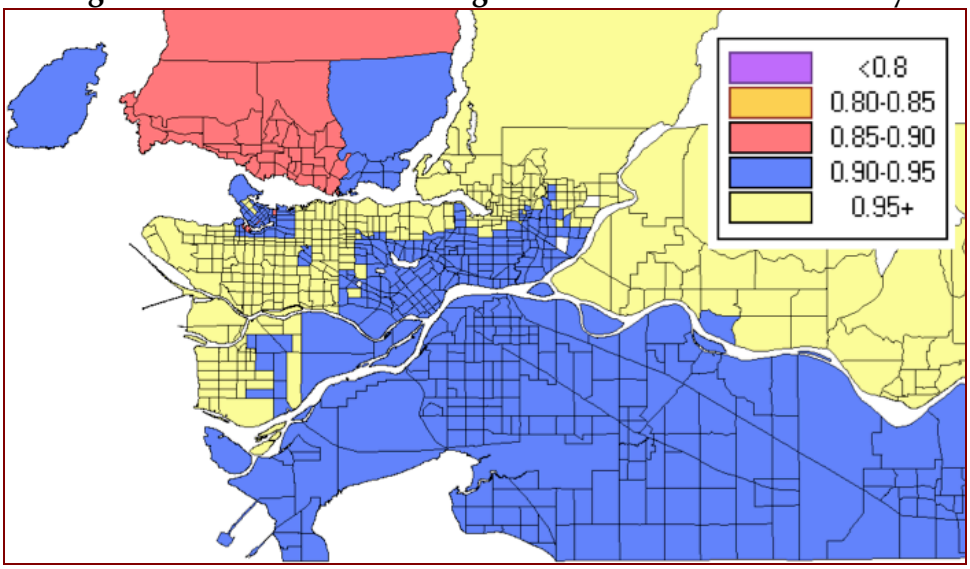


Figure 4.6: Lion's Gate Damage Outcome 2021 Accessibility

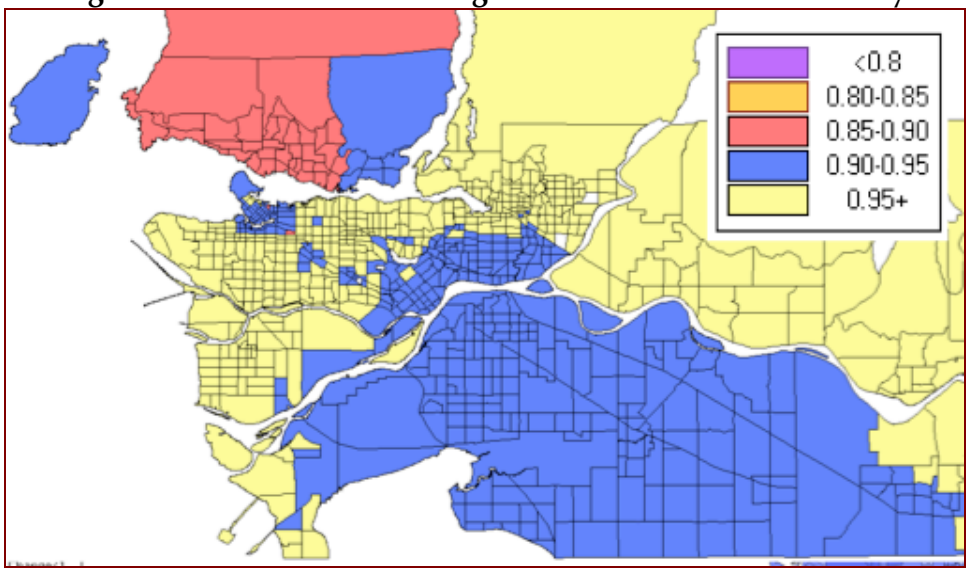
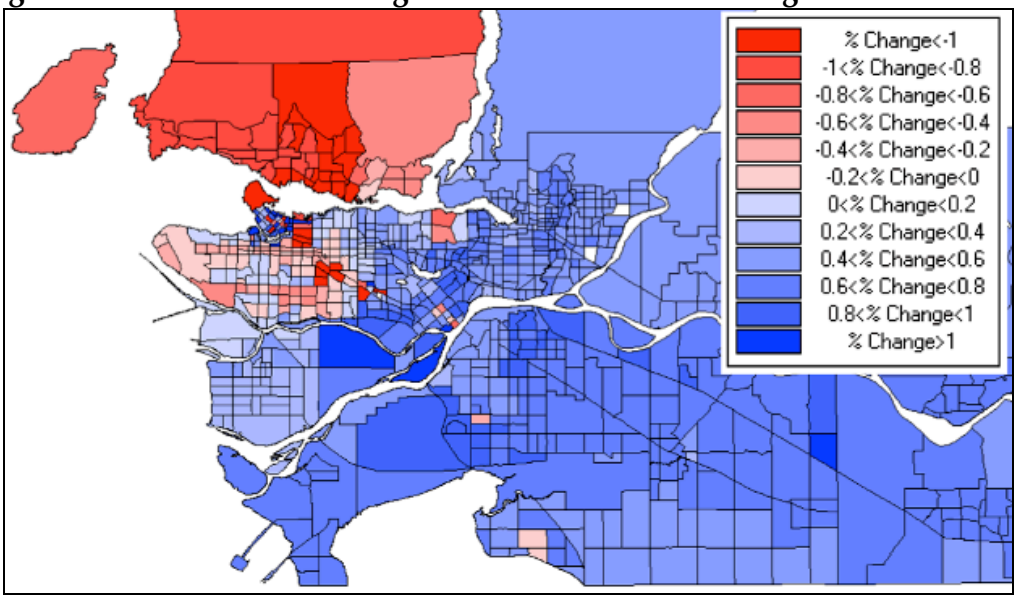


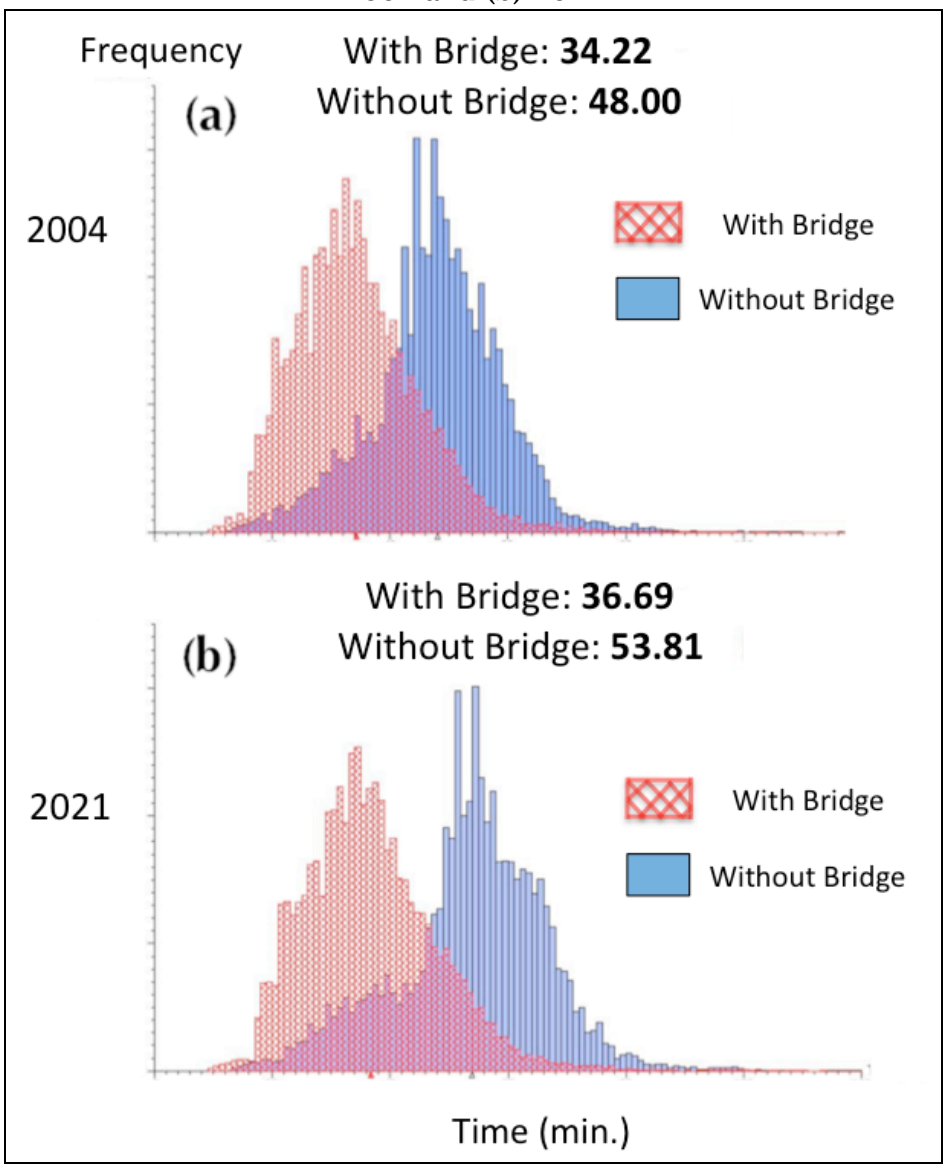
Figure 4.7: Lion's Gate Damage Outcome - Percent Change in Accessibility



4.2. Alex Fraser Bridge Damage Outcome

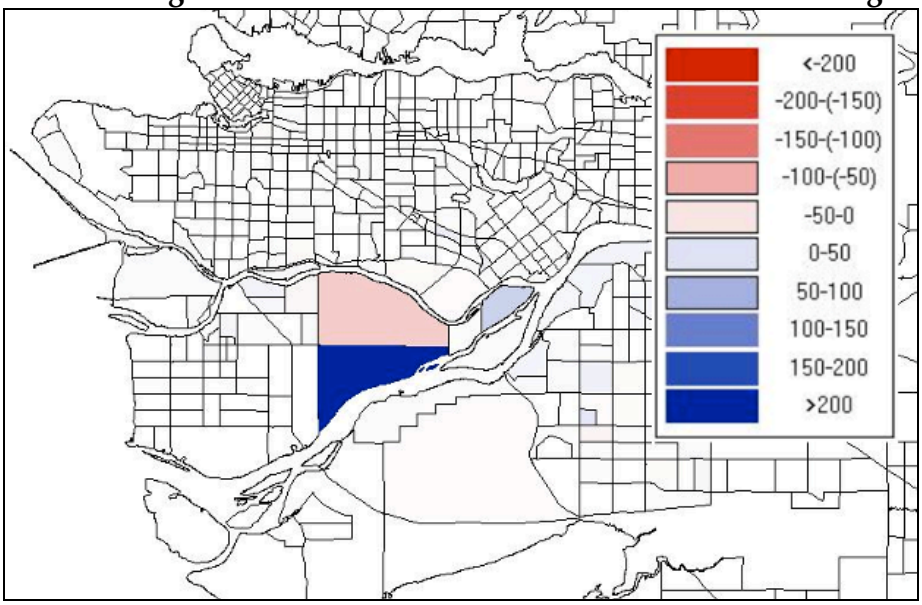
The closure of the Alex Fraser Bridge produces much different results, as compared to the previous scenario. The travel times for users of the Alex Fraser Bridge in 2004 before and after bridge closure were 34.2 and 48.0 minutes respectively. By 2021, travel times before and after closure were 36.7 and 53.8 minutes respectively (Figure 4.8). Unlike the Lion's Gate Bridge damage scenario which saw no change in the travel time increase over 17 years, the closure of the Alex Fraser Bridge produced travel time increases of 14 and 17 minutes in 2004 and 2021 respectively. This three minute increase between the two periods may seem insignificant, however it does shows that changes solely to a region land-use configuration can produce varying degrees of post-disaster transportation performance.

Figure 4.8: Pre- and Post-Earthquake Travel Times for Alex Fraser Bridge Users in (a) 2004 and (b) 2021



Results show that over 17 years, the demand for the Alex Fraser Bridge has increased 7.32% as the number of commuters grew from 5722 to 6141. Alex Fraser Bridge commuters travel to many destinations in Metro Vancouver in both 2004 and 2021, however as seen in Figure 4.9, the greatest increases and decreases in demand to zones are represented in blue and red respectively. Again, it appears the increase and decrease in demand to these zones are associated with large increases and decreases in total employment, respectively.

Figure 4.9: Change in Demand to Destinations for Alex Fraser Bridge Users



Regionally, the closure of the Alex Fraser Bridge produces a distribution of accessibility less serious as compared to the previous scenario. As seen in Figure 4.10 accessibility in 2004, for the most part, remains fairly high though areas such as West and North Vancouver, Vancouver, Richmond, and Burnaby see accessibility drop to between 0.90 and 0.95. As seen in Figure 4.11, by 2021 accessibility worsens for most of these areas including now all of Delta. Figure 4.12 shows that over time, changes to the regional form makes the loss of this bridge more severe, as represented by the intense red. In other words, the loss of this bridge presents greater concern for future transportation systems as the spillover of Alex Fraser Bridge commuters on to the surrounding road network in the future causes greater travel disruption.

Figure 4.10: Alex Fraser Bridge Damage Outcome 2004 Accessibility

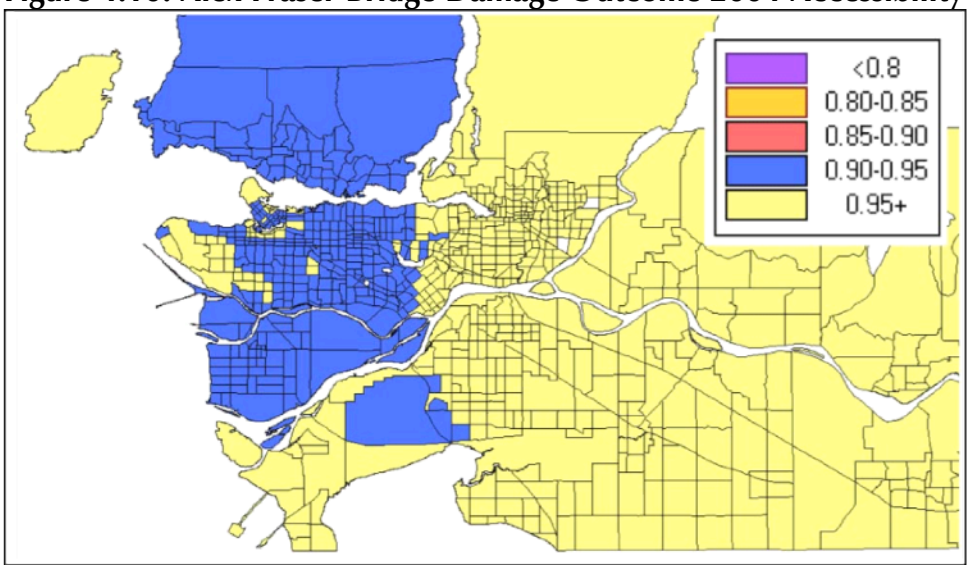


Figure 4.11: Alex Fraser Bridge Damage Outcome 2021 Accessibility

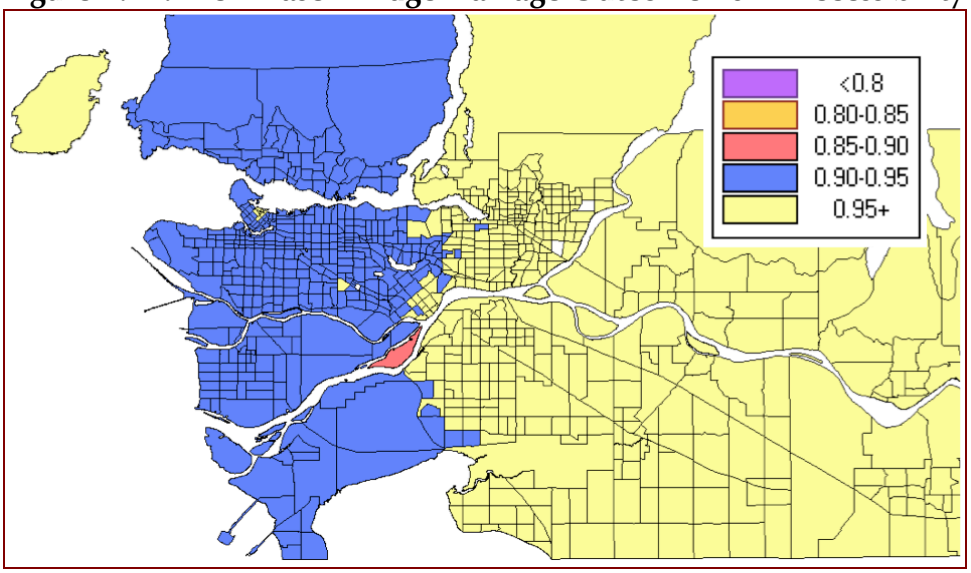
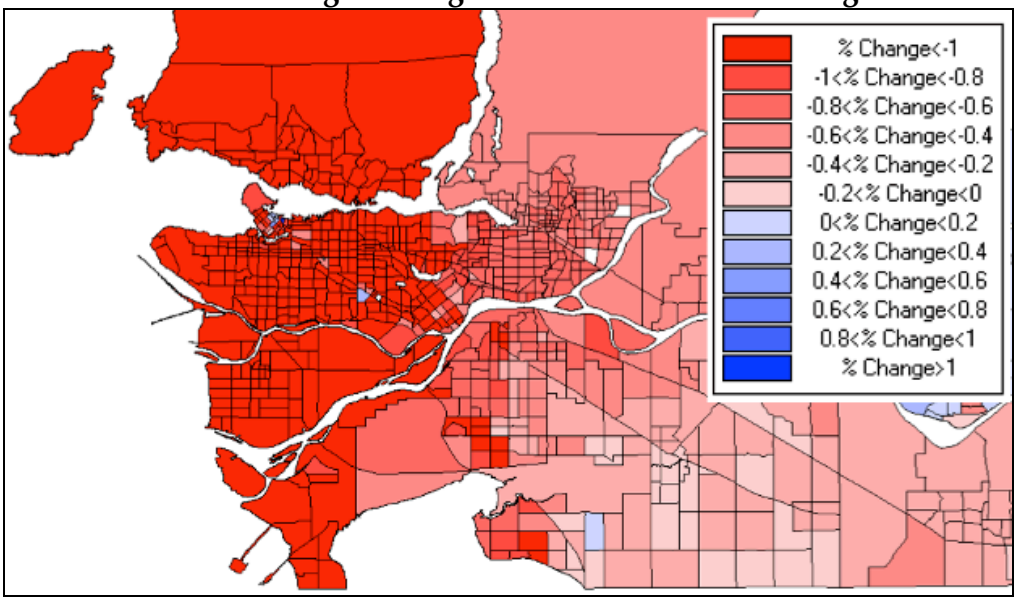


Figure 4.12: Alex Fraser Bridge Damage Outcome – Percent Change in Accessibility



4.3. Arthur Laing Bridge Damage Outcome

The closure of the Arthur Laing Bridge does not appear to cause significant travel disruption for its commuters. As seen in Figure 4.13 (a) and (b), the closure causes only a 5 and 6 minute increase in travel times for bridge users in 2004 and 2021 respectively. Findings show that there is a 4.96% increase in overall bridge usage. As seen in Figure 4.14, it appears that Arthur Laing Bridge users predominately travel to the areas including the Vancouver International Airport. Over time, these areas attract the greatest amount of commuters. The increase in demand to these zones appears to be a consequence of increases in total employment.

Figure 4.13: Pre- and Post-Earthquake Travel Times for Arthur Laing Bridge Users in (a) 2004 and (b) 2021

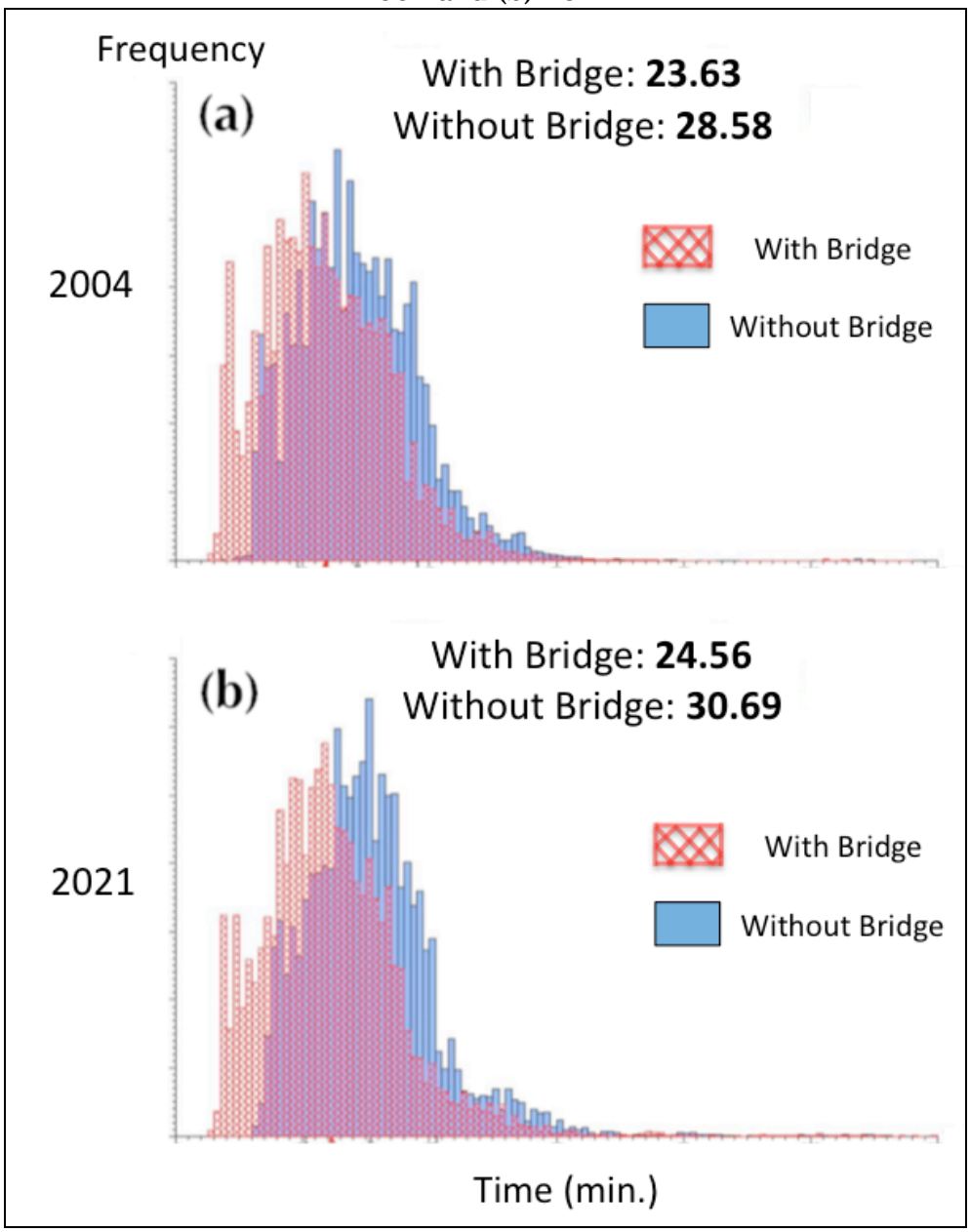
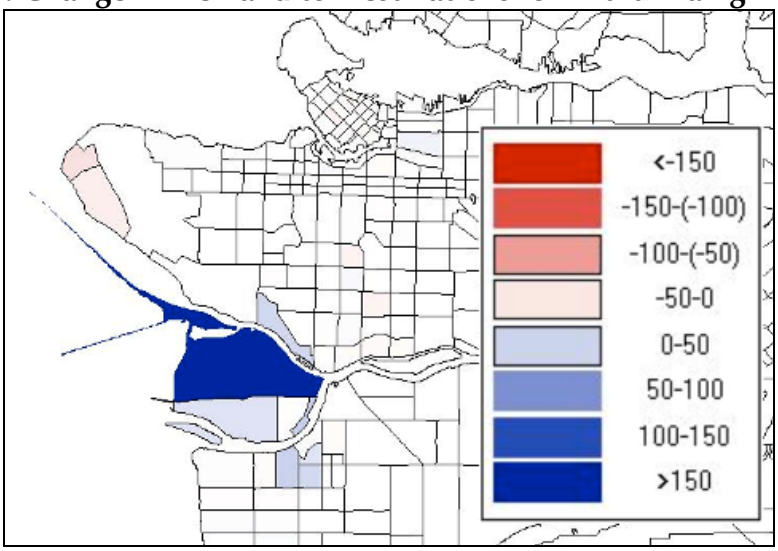


Figure 4.14: Change in Demand to Destinations for Arthur Laing Bridge Users



As seen in Figure 4.15, it would appear that the greatest loss of accessibility in 2004 is confined to areas located in Richmond. In particular, the areas represented in red and orange (i.e. Vancouver International Airport) see the greatest diminished transportation performance. As Figure 4.16 illustrates, in 2021 accessibility for these areas worsens, though values still remain high. Overall accessibility for most of the region, including Richmond and Delta, decreases between 2004 and 2021 as seen in Figure 4.17.

Figure 4.15: Arthur Laing Bridge Damage Outcome 2004 Accessibility

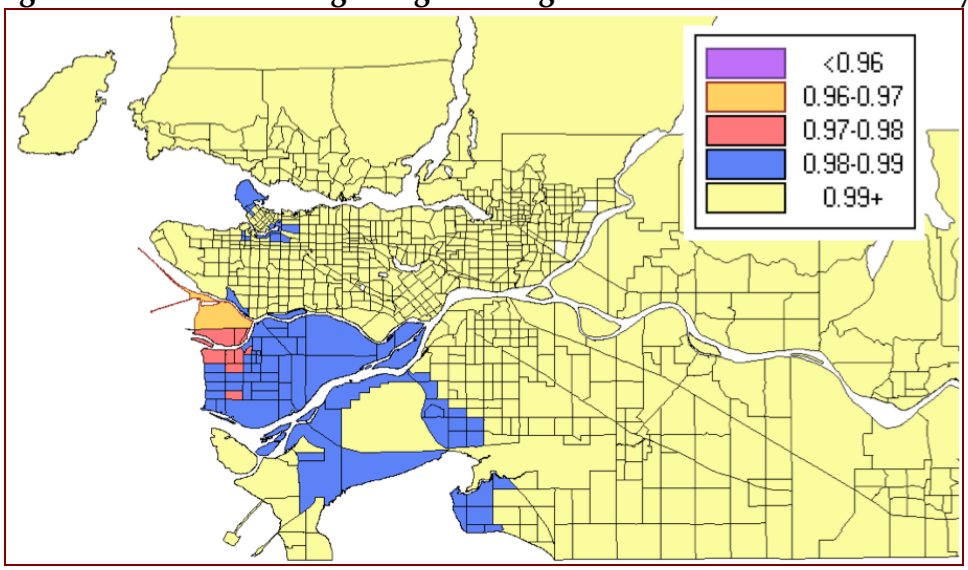


Figure 4.16: Arthur Laing Bridge Damage Outcome 2021 Accessibility

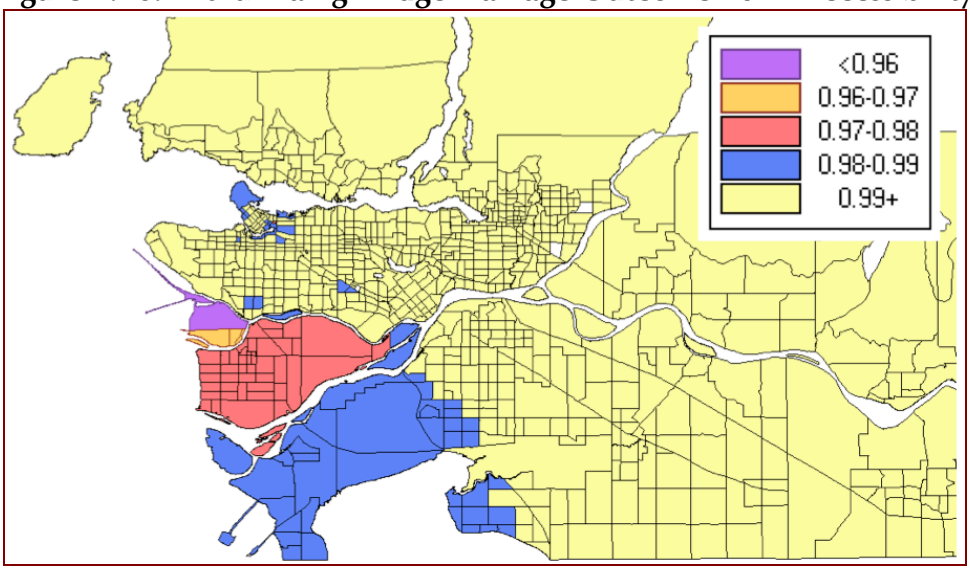
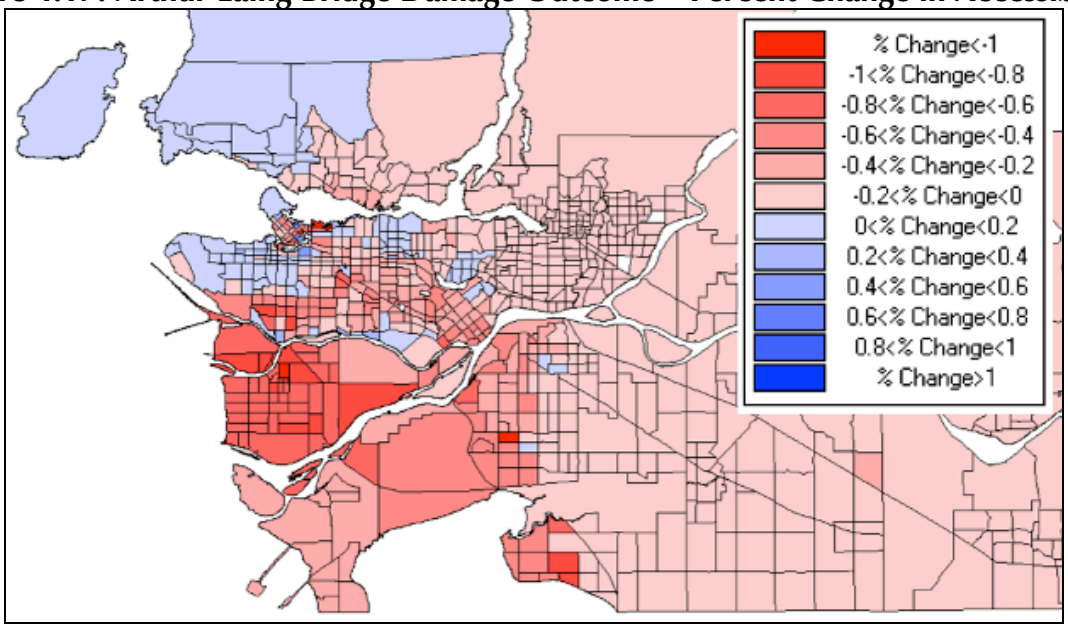


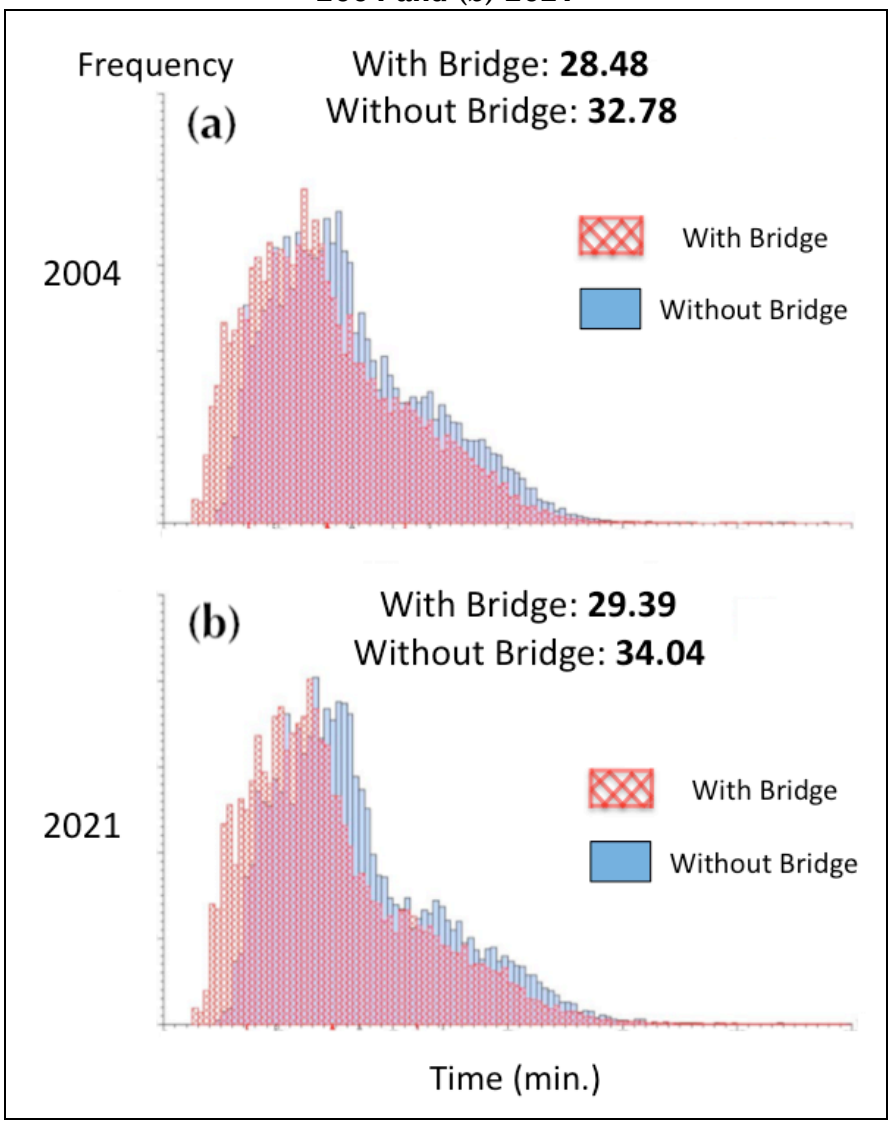
Figure 4.17: Arthur Laing Bridge Damage Outcome – Percent Change in Accessibility



4.4. Oak Street Bridge Damage Outcome

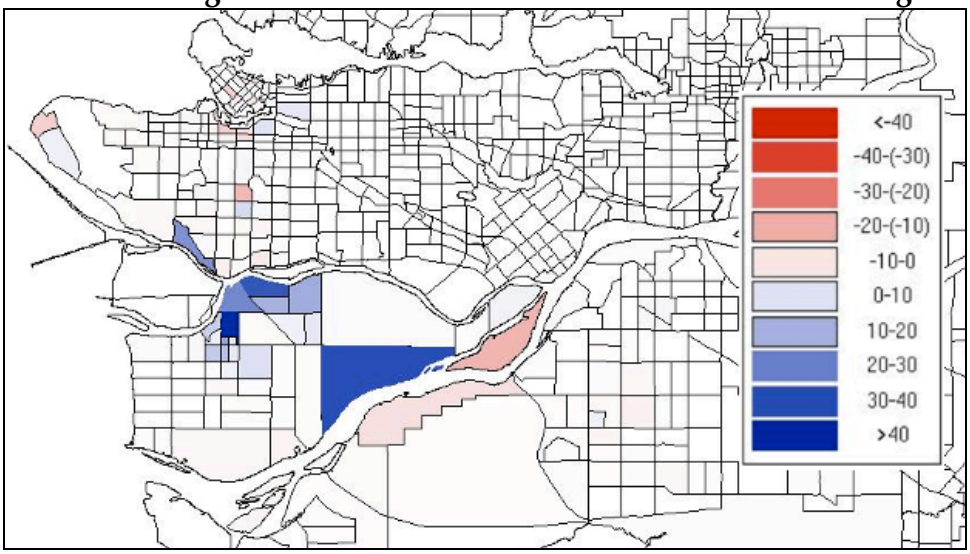
The closure of the Oak Street Bridge causes relatively minimal travel disruption for its users. As seen in Figure 4.18 (a) and (b), with its closure, travel times increase by 4 and 5 minutes in 2004 and 2021 respectively. Between 2004 and 2021, bridge usage increases by 4.65%.

Figure 4.18: Pre- and Post-Earthquake Travel Times for Oak Street Bridge Users in (a) 2004 and (b) 2021



Furthermore, as seen in Figure 4.19, bridge user commutes are predominately concentrated in northern Richmond. In fact, the greatest increase in demand is seen in zones which see increases in total employment.

Figure 4.19: Change in Demand to Destinations for Oak Street Bridge Users



Overall, as illustrated in Figure 4.20, the loss of the Oak Street Bridge appears to affect Richmond and Delta most severely, while parts of Mainland Vancouver, Burnaby, and North Vancouver experience some diminished transportation quality in 2004. As seen in Figure 4.21, by 2021 accessibility for Richmond and Delta get worse, though overall accessibility still remains relatively high. Over time, transportation performance appears to get worse, particularly for Richmond and Delta, as illustrated by Figure 4.22.

Figure 4.20: Oak Street Bridge Damage Outcome 2004 Accessibility

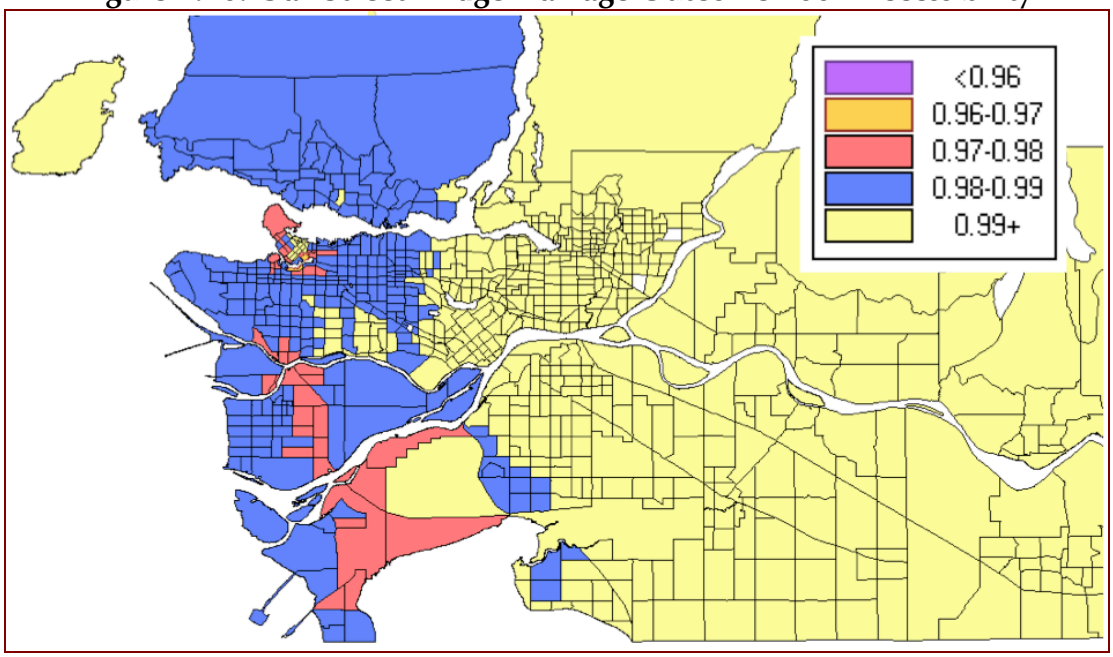


Figure 4.21: Oak Street Bridge Damage Outcome 2021 Accessibility

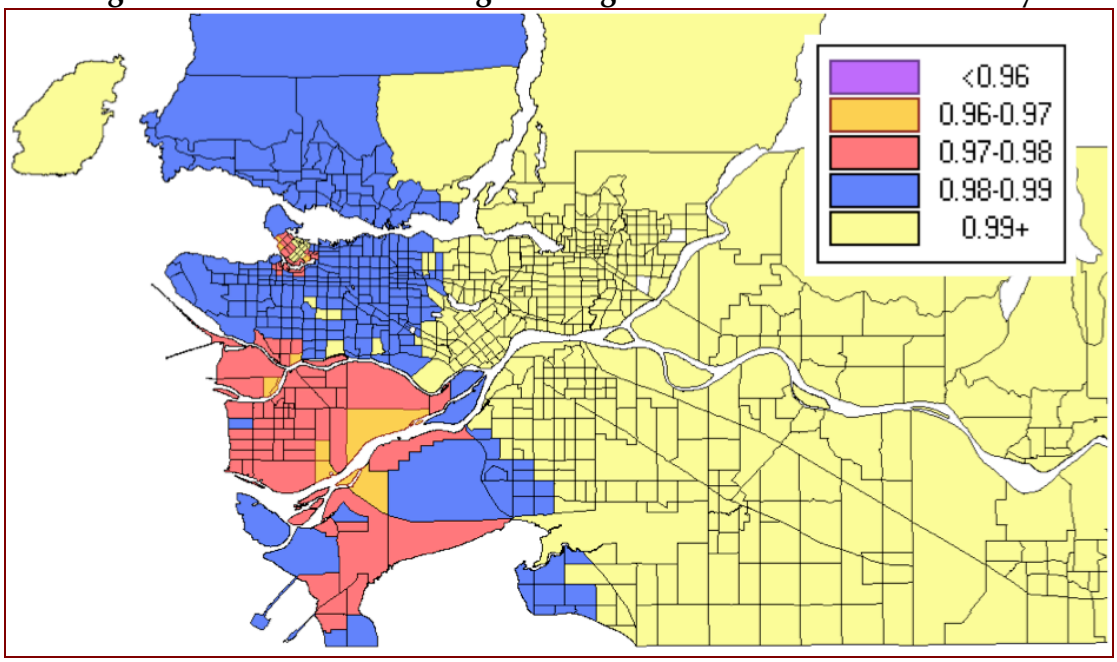
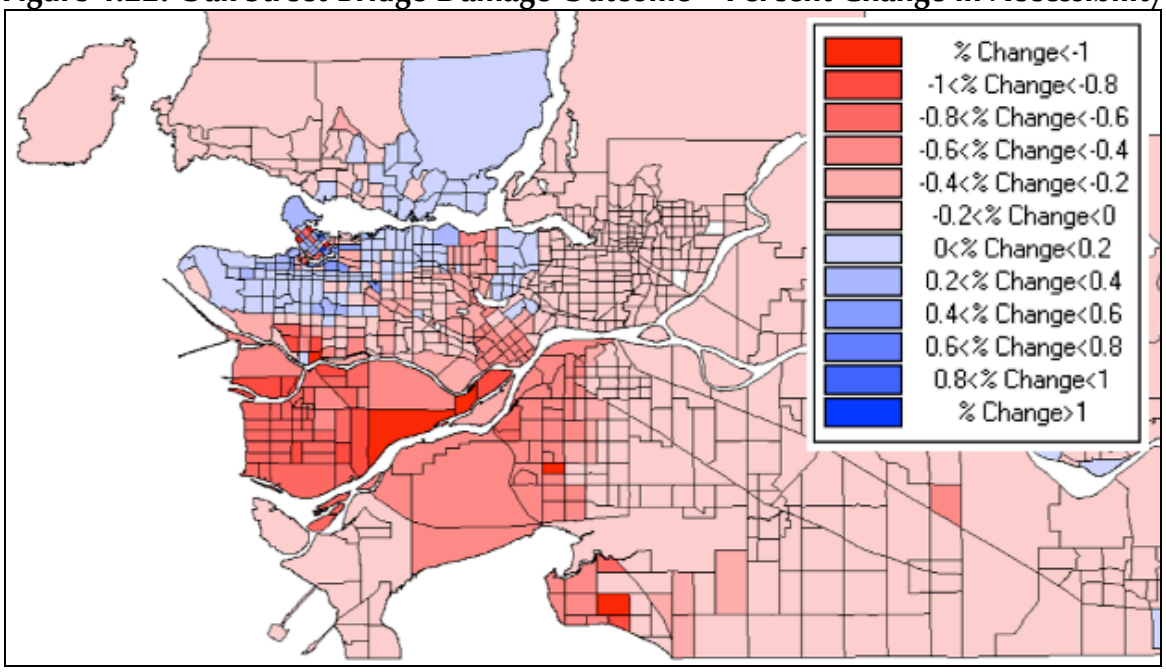


Figure 4.22: Oak Street Bridge Damage Outcome – Percent Change in Accessibility



Overall, these four damage outcomes present very different post-disaster transportation results. Summarized in Table 4.1 and Table 4.2, the Lion's Gate Bridge damage outcome show to be the most disruptive, however due to minimal changes to bridge utilization, future transportation systems will see accessibility increase. The loss of the Alex Fraser Bridge produces moderate travel disruption for both 2004 and 2021, however due to a relatively high increase in bridge usage,

future transportations will experience greater disruption. Lastly both the Arthur Laing and Oak Street Bridge damage outcomes produce relatively high accessibility values. Due to moderate changes in bridge utilization, future transportation systems will experience moderate declines in transportation performance in the future.

Table 4.1: Summary of Damage Outcomes (in Relative Terms)

Damage Outcome	Regional Accessibility (2004)	Regional Accessibility (2021)	Regional Change in Accessibility	Bridge Usage Change
Lion's Gate	Low	Low	Moderate Improvement	0.11%
Alex Fraser	Moderate	Moderate	Intense Decline	7.32%
Arthur Laing	High	High	Moderate Decline	4.96%
Oak Street	High	High	Moderate Decline	4.65%

Table 4.2: Summary of Average Travel Times (min.) for Bridge Users in 2004 and 2021

	2004			**2021**		
	With Bridge	Without Bridge	**Travel Time Change**	With Bridge	Without Bridge	**Travel Time Change**
Lion's Gate	26.0751	46.4115	**20.3364**	26.3708	47.2214	**20.8506**
Alex Fraser	34.2220	48.0033	**13.7813**	36.6925	53.8149	**17.1224**
Arthur Laing	23.6343	28.5829	**4.9486**	24.5631	30.6872	**6.1241**
Oak Street	28.4773	32.7813	**4.304**	29.3865	34.0446	**4.6581**

4.5. General Findings

In these results two broad themes have presented themselves. Specifically they are related to (1) how future land-use configurations either encourage or discourage bridge demand and consequent transportation performance, and (2) how surrounding networks are able or unable to adequately absorb an unexpected increase in demand.

At the crux of this research is the argument that cities invite some level of risk from hazards caused simply by changes to its regional form. In identifying such risks and its potential sources, perhaps we can properly prepare for them. An examination of how land-use configurations evolve over time perhaps best represents changes to the regional form. Between 2004 and 2021 certain land-use changes appear to make Metro Vancouver's transportation system vulnerable to earthquake hazards. Specifically, due to significant growth in total employment in various zones, the Alex Fraser, Arthur Laing, and Oak Street Bridge damage scenarios will produce greater transportation disruption in the future. Conversely, for most of the region, future land-use characteristics (i.e. balanced growth and decline of total employment), appear to make the loss of the Lion's Gate Bridge in 2021 more manageable than in 2004. In other words, Accessibility

values following the loss of the Lion's Gate Bridge for most of the region improve between 2004 and 2021.

In every damage scenario however, changes in accessibility between the two study periods are a function of changes in bridge utilization that result from changes in land-use. When observing how transportation performance changes over time, results suggest that changes in bridge utilization determine the extent of transportation quality in the future. For instance, between 2004 and 2021 the Alex Fraser Bridge sees usage increase 7.32%, which has resulted in intense reductions of accessibility throughout. Relatively moderate increases of 4.96% and 4.65% in bridge usage seen for the Arthur Laing and Oak Street Bridges respectively, have produced moderate reductions in accessibility. In general, as the number of bridge users increase, the spillover of commuters onto the surrounding network causes greater travel disruption, as seen in the Alex Fraser, Arthur Laing, and Oak Street Bridge damage scenarios. The Lion's Gate Bridge damage scenario is unique however, due to its relatively non-existent change in bridge usage. In fact, the reduced usage of this bridge, places less of a burden on future transportation systems, and is why accessibility over time improves. In 2004 the number of single occupancy vehicle (SOV) users of the Lions Gate Bridge was 4394 during a typical morning peak hour. However, despite a 21% increase in SOV ridership, which has increased system-wide demand for transportation infrastructure, by 2021 the number of users of the Lions Gate Bridge grew only by 0.11%.

Observing how transportation performance changes over time offers several insights. By first determining how performance diminishes over time, we can identify the zones which garner the greatest responsibility for reduced transportation quality. In identifying these zones, planners are given greater information which can be used in many ways. In particular, this information can be used in informing planners which areas may be unsuitable for intense employment or housing development. Or such findings can possibly help planners determine which areas are most suitable for down-zoning. But perhaps the most appealing aspect of this research is that by identifying which areas would contribute to the greatest increases in bridge utilization and subsequent diminished performance, targeted transportation demand management strategies and policies can be used to minimize future travel disruption. Such strategies will be discussed in further depth in the following section.

The second main theme from these findings is related to the transportation network's ability to absorb an unexpected increase in commuters. Each of the four damage scenarios presents different levels of network redundancy, which affect the severity of post-disaster transportation performance. At one end there is the Lion's Gate Bridge, which has a low network redundancy. At the other end are the Arthur Laing and Oak Street Bridges. The Alex Fraser is located somewhere

in-between. The Lion's Gate Bridge damage scenario produces the greatest transportation disruption, as a consequence of low network redundancy. The Arthur Laing and Oak Street Bridges damage scenarios see the least transportation disruption, likely due to their relatively high redundancy. The Alex Fraser Bridge damage scenario sees relatively moderate disruption, as a consequence of relatively moderate levels of redundancy. Based on these results, post-disaster transportation performance appears to be highly dependent on the level of network redundancy.

Chapter 5. Concluding Remarks

Overall this section will begin by summarizing the overall research conducted, in addition to (1) exploring the relevance of the results in pre- and post-disaster contexts, (2) discussing areas in this research which perhaps deserve improvement, and (3) examining prospects for future research.

5.1. Research Summary

Transportation systems are critical to any city or region. Studies have consistently demonstrated the importance of these systems in helping maintain community cohesion, financial stability, and even physical and emotional well-being (Frank and Engelke, 2001; Meyer and Miller, 2001; Hanson and Giuliano, 2004). Unfortunately however, when exposed to earthquake hazards, these systems have shown to be particularly vulnerable. As past events have taught us, events such as the 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes have all demonstrated the immense social and economical toll earthquakes have had on transportation systems (Chang and Nojima, 1997; Chang and Nojima, 2001; Horwich, 2000). If potential hazards in Metro Vancouver show to present similar consequences as other past disasters have demonstrated, it certainly deserves some attention. By understanding Metro Vancouver's exposure to earthquake hazards and commuter reliance on a potentially vulnerable bridge network, potential actions can be taken in order to minimize any devastating outcomes.

Revisiting the motivation for this research, we are reminded of the core research questions:

- How will transportation systems perform in various earthquake scenarios?
- How does post-earthquake transportation performance risk change over time?
- How does Metro Vancouver's regional form (or 'regional land-use configuration') contribute to transportation performance risk?
- Which areas in the region are subject to the greatest transportation risk?
- Which pieces of transportation infrastructure are most critical to minimizing risk?
- Which land-use configurations pose the least post-earthquake transportation disruption risk?

Overall, this research has shown that when exposed to sub-crustal earthquakes with magnitudes between 4 and 8, Metro Vancouver's suite of bridges are structurally resilient. Though there are low probabilities of damage of occurring, four of the most vulnerable structures highlight

some interesting findings related to the research questions. In attempting to answer these questions, two broad themes suggest that (1) network redundancy greatly affects post-disaster transportation performance, and (2) future land-use will determine the extent of disruption future disasters will be pose.

With regard to the former, this work shows that the most likely damage outcomes include the closure of the Lion's Gate, Alex Fraser, Arthur Laing, and Oak Street Bridges. Damage to these bridges presents an interesting array of outcomes for examining network redundancy. As demonstrated through these examples, network redundancy and post-earthquake transportation disruption are proportional. With respect to the latter theme, results show that in most cases, increases in bridge utilization caused by future land-use configurations, will make future disasters more disruptive (e.g. Alex Fraser, Arthur Laing, and Oak Street Bridge damage outcomes).

Perhaps the most valuable and innovative part of this research was the development of a methodological framework to study post-earthquake transportation performance for Metro Vancouver (using a social indicator like accessibility). This undertaking certainly required the collaboration of many individuals (particular those with expertise in the fields of engineering, transportation, land-use, and modeling), and demonstrated how multiple disciplines could be brought together to study a series of research questions. Laying the foundation for future work, other research questions can be examined using the general framework presented in this thesis. Another innovative aspect of this work is the study of post-earthquake transportation performance and land-use for both past and future regional forms. The findings of this work can provide some insights into how regional shifts in population and employment will affect transportation following an earthquake hazard. Other interesting implications of this research will be discussed in the following sections.

5.2. Implications of Research Findings

Overall, the findings produced from this research can be of use in some interesting ways. Firstly, the findings can help decision-makers determine which bridges are appropriate for pre-disaster retrofit or post-disaster reconstruction prioritization. Second, the findings can be used in identifying patterns of isolation. Last, the results can be used for the appropriate deployment of transportation demand management strategies.

5.2.1. Bridge Prioritization for Retrofit or Reconstruction

In terms of pre-disaster retrofit prioritization or post-disaster reconstruction, these four damage scenarios can provide decision-makers with valuable information regarding the region's

critical infrastructure. Certainly, actions to minimize the effects of infrastructure loss should be taken, however determining which bridges require such intervention, needs thoughtful consideration. These findings can help in this process. The loss of the Arthur Laing and Oak Street Bridges have low likelihoods of occurring, and due to their high network redundancy, travel disruption appears to be minimal. In terms of prioritization, perhaps these two are not candidates. The Alex Fraser Bridge has a moderate level of network redundancy, and will see the greatest increase in bridge demand. Taking into consideration future transportation systems and performance, perhaps this bridge is the most ideal candidate for retrofit or reconstruction priority. However, this research shows that the most vulnerable structure is the Lion's Gate Bridge, and its closure would cause significant travel disruption. Logically this would appear to be the most appropriate candidate for prioritization. What is important is that these results should not be considered in isolation. Other information should be consulted. For instance, though the loss of the Arthur Laing Bridge is less likely, given that this bridge acts as a connection to the Vancouver International Airport, its loss could have significant implications. After an earthquake emergency rations and aid may be required. Thus, this bridge may be of greater importance immediately after an earthquake. Overall, though there is no definitive answer as to which bridge is most appropriate for such measures, the research does provide decision-makers with valuable information, which he/she can use as they see fit.

Again, it should be noted that the bridge structural models used in this research do not account for retrofit improvements already performed on the 10 bridges under study. Rather, what this research presents is a methodology for rationally determining which bridges deserve pre-earthquake retrofit and post-earthquake reconstruction prioritization.

5.2.2. Identifying Patterns of Isolation

Given that a significant amount of commuters require the use of a bridge to get to their destinations, the unexpected loss of this type of infrastructure can leave many areas in complete isolation. This becomes increasingly important, especially when there is a need for emergency supplies and first responders. By identifying which areas will likely experience the greatest isolation, decision-makers can ensure that rations are available, so there is less of a need to ship supplies from outside sources. Based on preliminary findings, a likely damage scenario would see the closure of the Lion's Gate Bridge. The loss of this bridge appears to leave much of North and West Vancouver with diminished accessibility. Therefore, these municipalities would benefit greatly from ensuring their stockpile of emergency rations is ample, as sending aid from other areas would be difficult.

5.2.3. Application of TDM Strategies in Pre- and Post-Disaster Contexts

Often as regions change, particularly following a hazard, emerging transportation needs present themselves. Unfortunately, immediate infrastructure improvements can be extremely time-consuming and realistically infeasible in post-disaster circumstances. Thus, methods to manage transportation become increasingly relevant (i.e. increase efficiency). One broad technique for handling this type of transportation issue is transportation demand management (TDM) or 'mobility management'. By definition, transportation demand management is a "general term for various strategies that increase transportation system efficiency…. It emphasizes the movement of people and goods, rather than motor vehicles, and so gives priority to more efficient modes (such as walking, cycling, ridesharing, public transit and telework), particularly under congested conditions" (Litman, 2009). In essence TDM supports the idea that in order to 'solve' our transportation problems, we cannot simply keep building more roads and bridge, but rather we often need to curb demand. Though these types of strategies are employed by municipalities and regional districts to manage long-term transportation demand, perhaps these principles could be applied to a post-disaster transportation event. What was interesting to draw from the Pattullo Bridge closure was that commuters chose to leave earlier, heeding officials' suggestions. This is essentially a TDM strategy that helped keep normal rush-hour congestion low. There are several TDM strategies available to help manage the Metro Vancouver's transportation system more efficiently in post-disaster circumstances. For instance, some of these strategies can help (1) improve transportation options, (2) create incentives to use other modes and/or reduce driving, (3) manage parking and land-use more effectively, and (4) educate the public so they are more inclined to accept more 'targeted' TDM strategies.

It should be noted that TDM strategies often support the use of public transit. However, permanent public transit infrastructure (e.g. light and heavy rail) that is constructed for pre-disaster planning may in fact be vulnerable to earthquakes. In other words, though TDM advocates for public transit in order to reduce SOV usage, transit infrastructure (like bridge infrastructure) may be vulnerable to earthquakes themselves. Thus, before such investments in transit can occur, there should be further study and assurances this infrastructure can withstand a given earthquake.

5.2.3.1. Improved Transport Options

Though public transit has a myriad of benefits, including reducing road congestion and providing cheap alternative travel options which are environmentally sustainable, it is often stigmatized and labeled as inferior. As a consequence, there has been less urgency to promote

this mode of travel. Making public transit more efficient will make this mode more attractive to commuters, and hopefully make automobile travel less pronounced. This can be achieved by improving the overall quality of transit in the region. For instance, as the Victoria Transport Policy Institute (VTPI) describe, by increasing the "speed, frequency convenience, comfort, user information, affordability, and ease of access" this mode will be a very attractive means of travel. To encourage greater transit usage, there are several methods we can employ including (Litman, 2009):

- Have more service, more routes, increased frequency
- Have HOV priority using HOV lanes and bus ways
- Make comfort improvement, which reduce crowding, more comfortable seating, and cleaner vehicles
- Strategically choose optimal locations to place 'park-and-ride' facilities
- Improve security

An overall reduction of vehicles on road networks will reduce the intensity of transportation disruption in post-disaster contexts, as the system will increase its capacity to accept unexpected commuters.

5.2.3.2. Incentives to Use Alternative Modes and Reduce Driving

To create incentives for commuters to reduce the number of trips made or choose non-automobile transportation, methods could be generally viewed as 'carrots or sticks'. To change commuter behavior, we may choose to offer a reward or hand out a punishment. For instance, increased HOV lanes can encourage individuals to carpool, which generally give commuters quicker travel times. Road pricing would generate a similar outcome, however they are seen as penalizing the commuter. Though sticks may garner some resistance, often their effects are twofold as they can help reduce driving but also generate funding for other projects. Ideally we would not want to solely utilized only carrots or only sticks, but rather an appropriate combination. Some methods to encourage commuters to change their mode and reduce driving could by introducing priority lanes for HOV and transit. This could be applied to the region's arterial lanes. To encourage commuters to use 'active' modes of travel, such as biking and walking, it should be noted that merely having an adequate biking/walking infrastructure in place, does not mean that biking/walking will suddenly become the norm. Often there is a need to encourage this mode of travel. For instance, safer biking lanes, available storage, or shower stations at work could all make biking an appealing mode of travel.

5.2.3.3. Land-Use Management

With respect to long-term urban planning, one approach to transportation management is Transit-Oriented-Development (TOD) planning. This type of planning would have less immediate impacts, however it would lay the foundation for managing transportation effectively in the future. According to the Litman (2009), TOD "refers to residential and commercial centers designed to maximize access by transit and non-motorized transportation, and with other features to encourage transit ridership. A typical TOD has a rail or bus station at its center, surrounded by relatively high-density development, with progressively lower-density spreading outwards…which represents pedestrian scale distances". Again, it should be noted that transit infrastructure such as a rail or bus station needs to be able to withstand an earthquake, otherwise the transit investment's objective of being a post-disaster alleviator of travel disruption will not be realized. In summary this type of planning often advocates for:

- Mixed-use development
- Neighbourhoods are designed for biking and walking
- Interconnected Streets
- Compact Development
- Commercial Core
- Natural Open Spaces

This type of land-use management would be an effective method to reduce auto-oriented travel in the future and place less demand on some of Metro Vancouver's critical bridge infrastructure.

5.2.3.4. Public Education and Engagement

Introducing progressive transportation initiatives will undoubtedly see some sort of resistance. Considering our dependence on the automobile has been a pillar of our society and entrenched into our culture, it would be difficult to gain immediate support for this type of transportation management. As a consequence, it is critical that we ensure that information is available to residents, and we are actively engaging the community to convince that this is the most suitable transportation management for Metro Vancouver. In fostering certain travel behaviors, such as ridesharing or increased transit usage, transportation systems will be able to better handle abrupt commuter changes caused by a disaster.

5.2.3.5. 'Targeted' TDM Strategies in Disaster Planning

TDM strategies are generally unarticulated in disaster contingency plans. Instead, following the unexpected closure of certain infrastructure, commuters are bombarded with widespread pleas from government official to leave home earlier or carpool for instance (e.g. Pattullo Bridge closure). Though suggestions are sometimes heeded which in turn do minimize potential travel disruption, perhaps a more appropriate response would be to target those who are at the source of the disruption (i.e. bridge users). Though TDM strategies are seldom discussed in the realm of disaster planning, there are benefits in using them in either pre- or post-disaster contexts. What this research has demonstrated is that with reasonably accurate forecasts of future land-use scenarios, we can predict how transportation systems will fare following an earthquake in the future. Moreover, we can identify which areas would garner the greatest demand for certain road infrastructure. For example, as in the case of the Alex Fraser Bridge closure, we were able to identify three areas which attract the most commuters and consequently cause the greatest demand or utilization of a bridge (Figure 5.1). This is valuable information, particularly if decision-makers can use more targeted TDM strategies for these areas. By persuading employers in these zones to adopt such strategies, post-disaster travel disruption can be minimized, in addition to certainly saving them money and downtime.

Figure 5.1: Increases in Demand to Destinations for Alex Fraser Bridge Users

5.3. Areas of Improvement

Certainly any research that attempts to predict future events, assumes some level of error. Decisions with respect to data, models, and interpretation of results often require refinements.

Specifically, this section will suggest areas of improvement with respect to each of the three models.

5.3.1. Hazard Model Improvements

Though this research considers many earthquake hazard scenarios, with respect to location, depth, and magnitude, several others earthquake hazards were omitted. The hazard model generated sub-crustal earthquakes scenarios that originate in Metro Vancouver. This region is certainly vulnerable to both subduction as well as crustal earthquakes. To be more comprehensive, future research should consider how these types of earthquake hazards will affect transportation systems.

5.3.2. Structural Model Improvements

The structural models used for the ten bridges in this research were developed by FEMA (2003). It uses variables such as bridge length, age, and number of spans to classify each bridge. Though these models perhaps can reasonably determine the structural integrity of each bridge after an earthquake, having models developed specifically for each of the ten bridges would have been ideal. However creating a detailed structural analysis model for each bridge is a significant undertaking that is beyond the scope of this thesis.

Overall ten bridges were included in this analysis. They were initially chosen on arbitrary grounds, however further analysis suggested they were amongst the most critical in the region (as discussed in Section 3.2.2). Ideally to be fully comprehensive the model would have accounted for every bridge in the region.

5.3.3. Transportation Model Improvements

The transportation model only takes into account, single-occupancy vehicles. Though this mode accounts for the greatest proportion of commutes, travel by high-occupancy vehicles and transit are significant. Ideally, transportation performance would be able to account for all three modes, considering that following a disaster, individuals often alter their mode choice.

In identifying the locations which cause the greatest increase in travel disruption, 'increases in total employment' was often cited as the principle cause. Total employment is simply too broad a term. To describe changes to the regional form, perhaps the specific types of employment would have been more appropriate.

5.4. Future Research

Unfortunately, though attempts have been made to be as comprehensive as possible, not every research prospect could be examined to depths they certainly deserved. In fact, there are still some existing avenues of future research that stem from this work, which can be pursued.

5.4.1. Post-Disaster Transit Evaluation

In Metro Vancouver there have been signs the region is shifting further away from an auto-oriented transportation system. This is seen in the construction of expansive transit lines, increased walkways and bicycle lanes. In fact some have argued that initiatives such as the U-Pass are making public transit commonplace and creating a generation of bus riders (Pablo, 2009). With this shift towards transit, one interesting potential research prospect is to study the effects of an earthquake on transit lines and their users. An interesting focus would be on rail infrastructure such as the Skytrain. Presumably, one would not need to create several infrastructure models, but just one; assuming the structures which support transit-lines are the same. Ideally in examining transit, the transportation performance indicator would capture more than just SOV ridership. In fact, if for instance a transit line is severed, commuters will likely shift their mode. The transportation model is able to account for this, simply by performing a 'model equilibrium'. Presumably, if a sky try station is damaged, there will be an influx of auto and bus ridership. In doing this, one would likely need to produce a post-disaster multi-modal transportation performance indicator (as described in Section 3.2.3.3); a novelty in and of itself. Though the model will be able to capture mode shifts, reaching model equilibrium is time consuming (i.e. approximately 3 hours). Therefore, perhaps this approach is most ideal for a limited number of damage outcomes.

5.4.2. TDM Strategies in Business Contingency Planning

TDM strategies have the potential to greatly reduce the potentially devastating effects the loss of transportation infrastructure may have on small businesses, stores, universities, and even schools. Recently for instance, the expected increase in traffic during the 2010 Vancouver Olympic Games have forced many municipal school boards to close their facilities as many teachers were likely to have difficult commuting (CBC, 2009). The effects of the Vancouver Olympic Games produce conditions comparable to an earthquake. For example, the games had forced the closure of various bridges, certain roads were made available only for high-priority vehicles, and certain areas experienced total gridlock. A well-coordinated suite of policy initiatives, particularly after an earthquake, can help mitigate some of the detrimental

consequences of diminished transportation performance. Potential research could be to form TDM strategies customized for a hypothetical business firm. By evaluating the specific travel behavior of their employees, information used by businesses can (1) identify which employees would be more productive working from home, (2) identify appropriate park 'n' ride locations, and (3) identify which employees could potentially travel together. Overall, the well-coordinated deployment of these strategies and policies by businesses across the region could minimize regional disruption to economic activities and allow only essential vehicles to be on the road. Common strategies for maintaining transport performances includes telecommuting, ridesharing, opposite work schedule, flextime hours, and dynamic park 'n' ride locations.

5.4.3. Evaluation of Different Land-Use Configurations

One interesting research prospect is rather than examining the entire region's transportation system, one could study the affects of different land-use planning policy for a specific damage scenario. For instance, focusing on the Alex Fraser Bridge damage scenario one could work through several different land-use configurations. This would entail making adjustments to zone-level data in the transportation model. For instance, one could simulate the transportation effects of a land-use scenario which allows for high density residence (e.g. condominium). Another potentially interesting modeling scenario would be to make changes to the land-use configuration to capture a particular TDM strategy (e.g. increased transit usage for a given zone). In doing this, one can provide planners with optimal planning strategies which minimizes post-disaster transportation risk.

5.4.4. Application of Unified Reliability in Evaluating Post-Disaster Transport Performance

One interesting methodology to studying post-disaster transportation performance is the use of classical structural reliability analysis to obtain probabilities of bridge closures and subsequent transportation network performance. In Haukaas (2008) this was referred to as "unified" reliability analysis. The unified reliability framework evaluates post-earthquake transportation performance by introducing random variables into hazards models, infrastructure models, and downstream consequence models (i.e. transportation model). This is done in recognition of the fact that the behavioral characteristics of variables, which enter a model, are seldom understood with complete certainty. For example, a model can determine the likely epicenter of an earthquake, but often this location may reside outside expected bounds. The unified reliability framework is able to capture this uncertainty using first-order reliability method or 'FORM' analysis. As Koduru (2008) describes

this type of analysis is concerned with "uncertainties arising from the inherent randomness in nature (aleatory) and due to the lack of knowledge (epistemic)". What is particularly appealing about this approach is that each bridge under study has an associated 'importance vector'. The importance vector can rank each bridge in terms of importance for a given performance indicator. Obviously this would be of great use to decision-makers in terms of identifying which bridges are most critical for maintaining transportation performance. Furthermore, given that decision-makers generally would benefit from greater amounts of information, this type of analysis can use multiple performance indicators to determine which bridges are most critical. For instance, one indicator may look at which bridges are most critical with respect to regional disparities in transportation performance, total costs, and perhaps patterns of social isolation. With several indicators available, more holistic decisions can be made.

Sampling analysis to obtain probabilistic results is straightforward and is carried out in this thesis. However, sampling is computationally costly and does not provide the importance measures described above. Unfortunately, results with the FORM analysis approach have been unrealized. Several problems have hindered progress in using this methodology. In particular, the high level of intrinsic complexity within the transportation model appears to cause the greatest difficult. The FORM analysis depends upon a 'smooth' response function because the derivative of the function is used in the analysis algorithm. This condition seems to be violated by the complexity of the transportation model and should be further investigated. Moreover, it is noted that the reliability analysis approach requires the transportation network performance to be distilled to a single value.

In the future, perhaps developing a more simplified transportation model will yield better results using this approach. This can be done using the existing transportation model. Simplifying the model may require making some broad generalizations, which could lead to lowered accuracy. However, after establishing this methodology, the transportation model can slowly be scaled-up.

Bibliography

Atkinson, G. M. (2005). Ground motions for earthquakes in southwestern British Columbia and northwestern Washington: Crustal, in-slab, and offshore events. *Bulletin of the Seismological Society of America, 95*(3), 1027.

BC Ministry of Transportation. (2009). *Travel count data from Alex Fraser and Port Mann bridges between Jan. 11-31, 2009.*

Burby, R. J. (1998). Natural hazards and land use: An introduction. *Cooperating with nature: Confronting natural hazards with land use planning for sustainable communities.* (pp. 1-26) John Henry Press. Washington, DC.

Burby, R. J., & French, S. P. (1981). Coping with floods: The land use management paradox. *Journal of the American Planning Association, 47*(3), 289-300.

Chang, S. E., & Nojima, N. (1997). Highway system performance measures and economic impact. *Proc. of the 7th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems,* 4-7.

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

Chang, S. E. (2003). Transportation planning for disasters: An accessibility approach. *Environment and Planning A, 35*(6), 1051-1072.

Clague, J. J. (2001). The Nisqually earthquake: A wakeup call from south of the border. *JOURNAL OF THE ASSOCIATION OF PROFESSIONAL ENGINEERS AND GEOSCIENTISTS OF BC, 5*(5), 14-17.

Clague, J. J. (2002). The earthquake threat in southwestern British Columbia: A geologic perspective. *Natural Hazards, 26*(1), 7-33.

Deakin, E. (1991). Transportation impacts of the 1989 Loma Prieta earthquake: The Bay Bridge closure.

DePolo, C. M., & Slemmons, D. B. (1990). Estimation of earthquake size for seismic hazards. *Neotectonics in Earthquake Evaluation,* , 1–28.

EMME. (2007). *Overview of EMME.* INRO.

FEMA. (2003). *Multi-hazard loss estimation methodology earthquake model - HAZUS-MH-MR4 - technical manual.*

Frank, L. D., & Engelke, P. O. (2001). The built environment and human activity patterns: Exploring the impacts of urban form on public health. *Journal of Planning Literature, 16*(2), 202.

Giuliano, G. (2004). Land use impacts, of transportation investments. *The geography of urban transportation* (pp. 237-273) Guilford Press.

Giuliano, G., & Golob, J. (1998). Impacts of the Northridge earthquake on transit and highway use. *Journal of Transportation and Statistics, 1*(2), 1-20.

Godschalk, D. R., Kaiser, E. J., & Berke, P. R. (1998). Integrating hazard mitigation and local land use planning. *Cooperating with nature: Confronting natural hazards with land use planning for sustainable communities.* (pp. 85-118) John Henry Press.Washington, DC.

Godschalk, DR, Kaiser, EJ, Berke, PR. (1998). Integrating hazard mitigation and local land use planning. Pp 85-118.

Godschalk, D., Kaiser, E., & Berke, P. (1998). Integrating hazard mitigation and local land use planning. pp85-118. *Cooperating with Nature. Confronting Natural Hazards with Land use Planning for Sustainable Communities. John Henry Press. Washington, DC.*

Gordon, P., Richardson, H. W., & Davis, B. (1998). Transport-related impacts of the Northridge earthquake. *Journal of Transportation and Statistics, 1*(2), 21-36.

Haddow, G. D., Bullock, J. A., & Coppola, D. P. (2007). *Introduction to emergency management* Butterworth Heinemann.

Hanson, S., & Giuliano, G. (2004). *The geography of urban transportation* (3rd Ed. ed.) Guilford Press.

Haukaas, T. (2008). Unified reliability and design optimization for earthquake engineering. *Probabilistic Engineering Mechanics, 23*(4), 471-481.

Horwich, G. (2000). Economic lessons of the Kobe earthquake. *Economic Development and Cultural Change, 48*(3), 521-542.

Jansen, R. B. (1988). *Advanced dam engineering for design, construction and rehabilitation* Van Nostrand Reinhold, New York.

Koduru, S. D. (2008). *Performance-based earthquake engineering with the first-order reliability method.* Unpublished.

Krinitzsky, E. L., Gould, J. P., & Edinger, P. H. (1993). *Fundamentals of earthquake-resistant construction* Wiley-Interscience.

Levine, N., & Wachs, M. (1998). Factors affecting vehicle occupancy measurement. *Transportation Research Part A, 32*(3), 215-229.

Litman, T. (2009). *TDM strategies.* Retrieved Jan/3, 2009, from http://www.vtpi.org/tdm/index.php#TDM

Mahsuli, M., & Haukaas, T. (2010 (Forthcoming)). *Methods, models, and software for seismic risk assessment.* Unpublished

Meyer, M. D., & Miller, E. J. (2001). *Urban transportation planning: A decision-oriented approach* McGraw-Hill Science/Engineering/Math.

Mileti, D. S. (1999). *Disasters by design* Joseph Henry Press.

Olshansky, R. B., & Kartez, J. D. (1998). Managing land use to build resilience. *Cooperating with nature: Confronting natural hazards with land-use planning for sustainable communities* (pp. 167-202)

Onur, T., & Seemann, M. (2004). Probabilities of significant earthquake shaking in communities across British Columbia: Implications for emergency management. *Proceedings of the 13th World Conference in Earthquake Engineering, Vancouver, BC, Canada, Paper, 1065*

Pablo, C. (2009, August 20th). TransLink's U-pass yields hidden bonus. *Georgia Straight,* Retrieved from http://www.straight.com/article-248112/upass-offers-hidden-bonus

Schmitt, R. (1998). A brief overview of the Northridge earthquake and its transportation impacts. *Journal of Transportation and Statistics, 1*(2), v-vi.

Schwab, J., Topping, K. C., Eadie, C. C., Deyle, R. E., & Smith, R. A. (1998). *Planning for post-disaster recovery and reconstruction* American Planning Association.

Wang, J., & Krajczar, K. (1998). *GVRD EMME/2 transportation planning manual* GVRD Strategic Planning Department.

Wikipedia (2009). Various websites describing bridge characteristics. Retrieved from <http://en.wikipedia.org/wiki/Main_Page>

Zhang, J., Okada, N., & Tatano, H. (2006). Integrated natural disaster risk management: Comprehensive and integrated model and Chinese strategy choice. *JOURNAL OF NATURAL DISASTERS, 15*(1), 29.

Zhu, S., Levinson, D., Liu, H., & Harder, K. (2009). The traffic and behavioral effects of the I-35W Mississippi river bridge collapse. *Transportation Research Board Annual Meeting,* 09-2164.

Appendix A – Bridge Functionality

According to FEMA (2003), it is possible to determine the probability of being in various damage states for a given spectral acceleration. In order to ultimately get the 'bridge functionality' there are a few steps required. Overall, these calculations are able to convert discrete data into a continuous 'bridge functionality'.

To obtain the probability of laying in four possible damage states (slight, moderate, extensive, and complete) for a given bridge, FEMA (2003) describes that the following calculations and data will be required. Structural data including bridge class (HWB1-HWB28), number of spans (N), skew angle (α), and bridge length (L), were obtained for each of the ten bridges seen in Table A.1 (FEMA, 2003). Most of this data was readily available online, however some of this data (e.g. number of spans) were determined visually. The following steps were required to calculate the probabilities at each damage state.

Step 1: Obtain the following data: bridge class (HWB1-HWB28), number of spans (N), skew angle (α), and bridge length (L). It should be noted that bridge class refers to 28 possible classes FEMA (2003) has characterized depending on bridge age, design, materials etcetera.

Step 2: Evaluate the following modification factors:

-K_{skew} = sqrt[sin(90-α)]

-K_{shape} = 2.5 x S_a(1.0 sec) / S_a(0.3 sec)

-K_{3D} = 1+A/(N–B) A and B
(Values for A and B are provided in a lookup table, for a given bridge class)

Note:
K_{skew} is a modifier that affects skewness

K_{3D} is a "factor that modifies the piers' 2-dimensional capacity to allow for the 3-dimensional arch action in the deck"

K_{shape} is a factor that acts as a modifier that "converts cases for short periods to an equivalent spectral amplitude at T=1.0 second" (FEMA, 2003)

Step 3: Adjust ground shaking medians for the 'standard fragility curves'

New S_a[1.0 sec] [for slight] = Old S_a[1.0 sec] [for slight] *$Factor_{slight}$

Where $Factor_{slight}$ = 1 if Ishape = 0 (I_{shape} from manual lookup table) OR
$Factor_{slight}$ = minimum of (1, K_{shape}) if Ishape = 1

New S_a[1.0 sec] [moderate] = Old S_a[1.0 sec] [for moderate] * (K_{skew}) * (K_{3D})

New S_a[1.0 sec] [extensive] = Old S_a[1.0 sec] [for extensive] * (K_{skew}) * (K_{3D})

New S_a[1.0 sec] [complete] = Old S_a[1.0 sec] [for complete] * (K_{skew}) * (K_{3D})

It should be noted that the '**Old S_a[1.0 sec]**' is provided in a lookup table in the manual, specific for each bridge class. For instance, a bridge class of HWB17 would have an Old S_a[1.0 sec] for slight, moderate, extensive, and complete damage of 0.25, 0.35, 0.45, 0.7 respectively.

Step 4: Determining Damage State Probabilities
-Using lognormal functions with these New S_a medians and betas of 0.6 (specified by manual) the probability of no damage, slight damage, moderate damage, extensive damage, and complete damage can be determined.

Step 5: Calculation of Bridge Functionality
-Discrete restoration functions produced by FEMA (2003) yields a 'Percent Bridge Functionality' for each damage state following a restoration period. Together with the probability of being in each damage state, determined in the previous step, one can form a relationship comparable to Figure A.1. Fitting a lognormal distribution to the discrete data, yields continuous bridge functionality data.

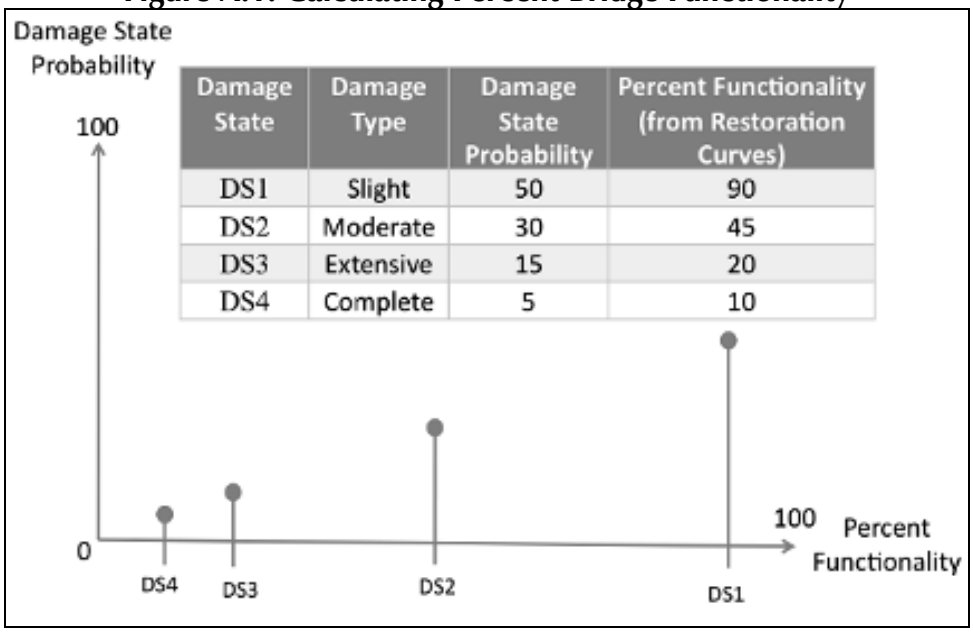
Overall these steps can convert discrete damage state probabilities to a continuous bridge functionality term. It should be noted that using a rounding threshold, bridge functionality terms will be converted to a binary value.

Table A.1: Bridge Classification Data

Bridge ID	Bridge Name	Built Year	Design	Total Length	HWB Class	Angle of Skew	# of Spans	Material	Bridge Retrofit
1	Alex Fraser	1986	Cable-stayed bridge semi-fan arrangement	2,602 m	5	85	3	Steel (cables, deck) Reinforced concrete (pylons, deck slab)	No
2	Arthur Laing	1975	Cantilever truss bridge hollow box, hunched	1,676 m	17	90	5	Pre-stressed concrete (Deck)	Yes
3	Burrard	1932	Truss bridge/ Vertical lift bridge	1,000 m	15	90	3	Steel (tower, truss)	Yes
4	Cambie	1985	Girder Bridge / Road bridge	1,100 m	10	90	5	Concrete	Yes
5	Granville	1954	Cantilever Truss Bridge	800 m	15	90	3	Steel (truss)	Yes
6	Ironworkers' Memorial	1960	Truss/ Cantilever truss bridge	1,292 m	15	90	7	Steel (truss)	Yes
7	Knight Street	1974	Girder bridge	1,450 m	10	90	3	Concrete	Yes
8	Lion's Gate	1938	Suspension Bridge/ gravity-anchored, deck truss	1,823 m	12	85	3	Steel (superstructure, cables, pylons, deck truss)	Yes
9	Oak Street	1957	Girder bridge hollow box, hunched	1,300 m	12	90	3	Steel (girder)	Yes
10	Port Mann	1964	Arch bridge orthotropic deck	2,095 m	15	90	3	Steel (Deck, arch)	No

Source: FEMA, 2003; www.wikipedia.org, 2009; BC Ministry of Transportation, 2009

Figure A.1: Calculating Percent Bridge Functionality



Damage State	Damage Type	Damage State Probability	Percent Functionality (from Restoration Curves)
DS1	Slight	50	90
DS2	Moderate	30	45
DS3	Extensive	15	20
DS4	Complete	5	10