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EXAMINING EARTHQUAKE-RELATED TRANSPORTATION DISRUPTION IN METRO VANCOUVER

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ABSTRACT

A convergence of several factors has made Metro Vancouver's transportation system vulnerable to earthquakes. Unfortunately, traditional post-disaster evaluation is often inadequate as they under-value regional dimensions of transportation quality. After a preliminary examination of ten of Metro Vancouver's critical pieces of infrastructure using a 'unified reliability' framework, results suggest that the transportation system will perform reasonably well. However, certain damage scenarios leave many areas with limited accessibility. 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, which could have significant social and economical consequences.

Introduction

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. For instance, 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). More recently, thousands of commuters in Minneapolis experienced extensive travel disruption following the unexpected collapse their I-35W Bridge (Zhu et al., 2008). The loss of transportation infrastructure clearly has significant implications to a region and its commuters. In fact, this was observed in Metro Vancouver in early 2009 when the abrupt closure of a bridge 'created havoc for rush-hour commuters' (CBC, 2009). As a result of a fire, the closure caused significant disruption for many commuters, and illustrated how the unpredictable loss of even a single piece of transportation infrastructure could have very disruptive consequences.

Several factors make Metro Vancouver's transportation system uniquely vulnerable to an earthquake hazard. These include (1) the region's close proximity to the Cascadia subduction zone, (2) commuters' heavy reliance on an extensive bridge network, and (3) increased demand on transportation systems as a consequence of population growth in every municipality in the region (Figure 1).

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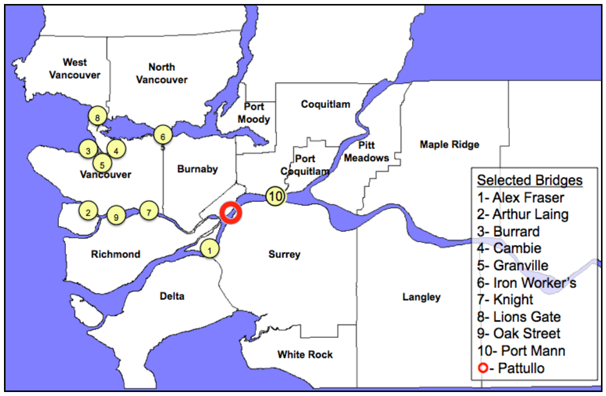

Figure 1: Study Area and Bridge Locations

Given Metro Vancouver's potential exposure to earthquake hazards, as well as its reliance on bridges, this research plans to study the effects earthquakes will have on regional transportation infrastructure and flow patterns. Overall the principle research objectives are to:

- Develop a methodology for evaluating post-earthquake transportation performance using a 'unified reliability' framework
- Understand how transportation systems will perform in various earthquake scenarios
- Determine which areas in the region would garner the greatest transportation risk
- Understand how post-earthquake transportation performance changes over time
- Determine which pieces of infrastructure are most critical to minimizing disruption

Metro Vancouver's regionally operated transportation authority, Translink, is responsible for the planning, management, and financing of virtually all of the region's transportation activities and infrastructure (Translink, 2009). Fortunately, they have provided this research with the Metro Vancouver transportation model for 2004 and 2021. Using a transportation model that is currently being employed by Metro Vancouver certainly adds assurances that the original data being analyzed is accurate. However, it should be noted that some of this data will be manipulated in order to replicate post-earthquake transportation conditions. To model the transportation system, a state-of-the-art forecasting model referred to as EMME/3 is being used.

2. Research Methodology: Unified Reliability Framework

In the ongoing work, the evaluation of post-earthquake transportation performance is conducted within a 'unified reliability' framework. This approach is specifically aimed at accounting for the uncertainties that are unavoidably present in predictions about future events. The two key ingredients in this approach are a) probabilistic models and b) reliability methods. The probabilistic models employ random variables to characterize the uncertainty, and the reliability methods are utilized to obtain event probabilities. Several useful by-products of this reliability analysis approach are also available (Haukaas, 2007).

The behavioral characteristics of the variables that enter a model are seldom understood with one hundred percent 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, typically by identifying variable characteristics such as mean, standard deviation, and distribution type. As illustrated in Figure 2, the probabilistic models in the unified reliability framework consist of (1) a hazard model, (2) a bridge structural model, and (3) a transportation model, each of which will be discussed in further depth. It should be noted that in the present analysis uncertainty only enters into the hazard and bridge structural models. In fact, in this paper the scope is limited to the evaluation of post-earthquake transportation performance by conducting a sampling analysis of several thousand disaster scenarios rather than carrying out reliability analysis.

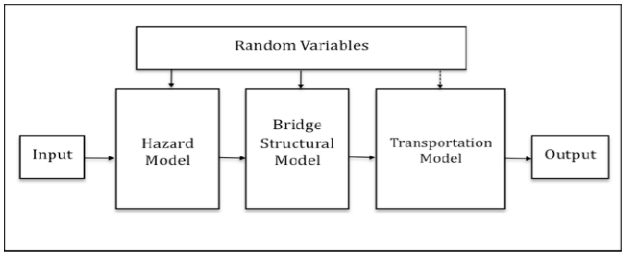

Figure 2. Unified Reliability Framework

2.1. Hazard Model

The hazard model generates earthquake scenarios characterized by epicenter location, magnitude, and subsequent site-specific intensity. The location model may be a fault line or an area source. In the preliminary analysis carried out in this paper, it is assumed that the epicenter will have a sub-crustal area source. With respect to the strength of potential earthquakes, the seismic moment magnitude will be between 5 and 8. Finally, to calculate the intensity of shaking at various bridge sites, attenuation algorithms developed by Atkinson (1995) were used. These algorithms were developed specifically for this region in order to determine a localized spectral acceleration. The spectral acceleration information is relayed to the structural model to determine if a bridge is able remain intact following an earthquake.

2.2. Bridge Structural Model

Bridges, especially in a region like Metro Vancouver, are critical pieces of infrastructure. Due to the region's unique geography, particularly the amount of water bodies present, commuters have relied 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, other road links, such as at-grade infrastructure, was omitted from this research. Certainly every bridge within the region is at risk of failure following an earthquake, but not every bridge could be included in this analysis. The principle reason for limiting the number of bridges was due to modeling constraints. For this reason only ten bridges were included in this analysis. They are the Alex Fraser, Arthur Laing, Burrard, Cambie, Granville, Iron Worker's, Knight, Lions Gate, Oak Street, and Port Mann Bridges seen in Figure 1.

Due to several reasons these bridges are among some of the most critical pieces of infrastructure in the region. Firstly, all ten bridges help maintain regional connectedness as each links various municipalities and major sub-areas. Secondly, each bridge is contained within an area of low network redundancy. Each of these bridges span 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, if an area has a low network redundancy, commuters moving from point A to B are restricted in the number of route options available. 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 higher daily traffic.

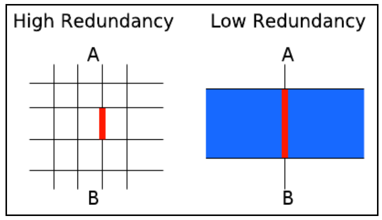

Figure 3. Road Network Redundancy Illustration

Each of the ten bridges have been assigned a structural model, which uses the spectral acceleration data produced by the previous intensity model to determine the extent of damage a bridge would experience following an earthquake. Using a bridge classification scheme developed by HAZUS (2003), information about structure type, skew angle, number of spans, and length were used to classify each bridge into one of 28 possible classes. In turn, each bridge class is associated with a set of 'fragility curves' that essentially provides the probability of being in five potential damage states for given ground motion intensity. The damage states are (1) None, (2) Slight/Minor, (3) Moderate, (4) Extensive, and (5) Complete.

Ultimately, using the probability of lying in each damage state, together with various restoration algorithms developed by HAZUS (2003), a link capacity for each bridge is determined. The link capacity is in reference to the percent functionality of each bridge after a given restoration period. It 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 of 0 would indicate the bridge is damaged and none of the lanes are available for use. Theoretically, link capacities can be a continuous number between 0 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 the most compelling argument for using the 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 certainly 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. Thus, if a bridge experiences any damaged, the link capacity is lowered to zero to represent a link closure. If a bridge is deemed to be structurally intact, it will be unaltered. Given that a total of 10 bridges are being examined, a binary approach would yield 1024 possible damage scenarios that will be used by the transportation model.

2.3. Transportation Model

The transportation model is the final component within the unified reliability framework. This model is used to ultimately determine how users' travel behavior would respond to a damaged road network. The unexpected loss of major transport facilities can produce a myriad of commuter behavior responses, from simply changing travel route, mode, time, or destination, to reducing trip-making frequency. In the aftermath of the 1994 Northridge earthquake, Giuliano and Golob's (1998) examination of two extensively damaged highway corridors, found that for the most part, commuters responded to this transport disruption by choosing to change their travel route. This research assumes that a similar post-earthquake response would occur, whereby damage to specific links will compel travelers to alter their route choices. Consequently, this will lead to increased congestion and travel disruption.

Predicting travel behavior has been of interest to transportation planners and engineers for nearly half a century (Meyer and Miller, 2001). Though technological advances, data acquisition improvements, and innovative analysis techniques have all made the process more efficient and accurate, the classic 'four-step model' has remained largely intact (Meyer and Miller, 2001). This model has an extreme 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, the following sub-models perform these tasks within the EMME/3 software: (1) Trip Generation, (2) Trip Distribution, (3) Mode Split, and (4) Trip Assignment. The outputs of this model are travel times and volumes on links and between zones during peak weekday morning periods for single-occupancy vehicle travelers in 2004 and 2021. Overall the model will be able capture travel congestion and disruption as a consequence of various bridge failures.

2.3.1 Transportation Model Verification: Pattullo Bridge Closure

The transportation model requires some manipulation to answer the principle questions in this research. The model attempts to replicate post-earthquake travel conditions, however outside an actual earthquake occurring, there are few events which allow us to test whether the modeling procedures are accurate. Fortunately for this research, on Sunday January 18th 2009 a fire had burnt a section of the Pattullo Bridge's wood trestle. Immediately following its closure, travel disruption was seen across parts of the region. The Pattullo Bridge (Figure 1) is one of Metro Vancouver's smaller bridges, which connects the cities of Surrey and New Westminster across the Fraser River. 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 an opportunity for model verification. This event is particularly interesting since it has essentially replicated 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 have obtained travel data from the Ministry of Transportation (MoT). Travel data was available for the weeks before, during, and after the bridge closure. The travel data was acquired from permanent count stations located at the (1) Port Mann Bridge and (2) Alex Fraser Bridge. Traffic volume data obtained from the Port Mann and Alex Fraser Bridges are of particular interest as they are situated on either side of the Pattullo Bridge and are relatively convenient alternatives to get across the Fraser River. 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. After removing the Pattullo Bridge from the transportation model, forecasted traffic volumes on the Port Mann and Alex Fraser Bridges increased by 33% and 31% respectively (Table 1) during a typical weekday morning peak hour.

Table 1. Vancouver Transportation Model: Bridge Volume Change

	Pre-Closure Volume	**Post-Closure Volume**	**% 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 MoT, 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). However, after further examination of Figures 4(a) and (b), 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%. It would appear that though the predicted versus actual volumes do not match up with respect to time, it does appear that the magnitude of change is consistent with what was modeled.

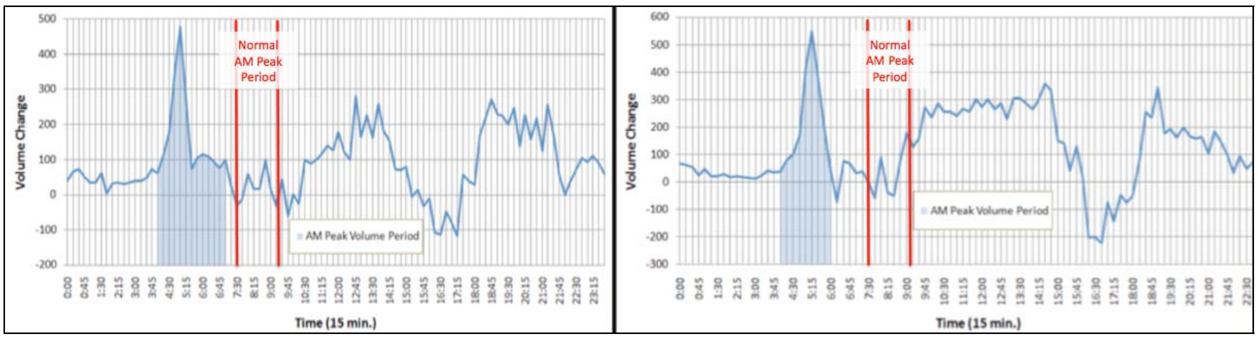

Figure 4. (a) Port Mann and (b) Alex Fraser Volume Change; Source: British Columbia Ministry of Transportation

2.3.2. Transportation Model Performance Indicator

Due to the nature and specific characteristics an earthquake presents, it can be extremely difficult to effectively measure subsequent transportation quality. System performance measures, such as localized travel congestion, are often used in transportation planning as a means of evaluating regional network quality, but are generally not used when evaluating post-earthquake transport quality. In contrast, a typical post-earthquake evaluation takes more of a single-component approach in assessing network elements (e.g. damaged bridges). Though site-by-site assessment is structurally critical for safety purposes, this approach overlooks many transportation related concerns (Chang, 2003). For instance, this type of evaluation may not consider the affect an earthquake may have with regards to post-disaster regional isolation patterns.

To evaluate post-disaster transportation quality, an ideal indicator would (1) minimize evaluation subjectivity, (2) be easily comprehensible, (3) be easily comparable across varying damage scenarios, (4) require minimal model run time, and (5) be represented at the zone level. A measure proposed by Chang and Nojima (2001) meets all of these criteria. Their work had proposed a post-earthquake system performance measure, which was based on the concept 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", measured through travel time (Chang and Nojima, 2001; Chang, 2003). Accessibility is the ratio of travel time between origindestination (O-D) pairs on a damaged network to the travel time on an undamaged network. This would produce values between 0 and 1, which would signify that the transportation system is non-functional and fully functional respectively. It should be noted that not all travel between O-D pairs are treated equally. To minimize any distortion caused by low demand (i.e. less significant) commutes, travel times between O-D pairs are weighted by travel volumes.

3. Results and Discussion

After conducting various sampling analyses, which in total generated 10,000 earthquake scenarios, results show that for the most part, the Metro Vancouver transportation system performs fairly well under hazardous conditions. Overall there is a 69.9% probability that none of the ten bridges will experience any damage. Of the potential damage scenarios, the most structurally vulnerable links appear to be the Lions Gate, Alex Fraser, and Oak Street bridges, with probabilities of failure of 2.06, 1.91, and 1.82 percent respectively. Though other damage scenarios occur, these three appear to be the most prominent. Determining which areas of Metro Vancouver would suffer the greatest travel disruption is a central objective of this research. Figures 5 through 7 illustrate this for each of the three likely damage scenarios mentioned previously.

Figures 5(a) and (b) show regional accessibility following the loss of the Lions Gate Bridge for two different periods. Damage to this bridge would understandably leaves parts of West and North Vancouver with diminished accessibility. To a lesser degree, travel to parts of Vancouver, Burnaby, Richmond, Delta, Surrey, White Rock, Coquitlam, Port Coquitlam, and Langley are limited as well. Much of this disruption in both study periods is reflective of low network redundancy. Though diminished accessibility is widespread, Figure 5(c) shows that change in accessibility over time between 2004 and 2021 improves, as indicated by the blue. Interestingly, this figure suggests that over time, the loss of the Lions Gate Bridge becomes less critical for the majority of Metro Vancouver. This improvement in accessibility is based purely on changes to the urban environment. This would suggest that users of the Lions Gate Bridge become less attracted to certain destinations as a consequence of changes to regional land-use. As seen in Figure 6(a) and (b), the loss of the Alex Fraser Bridge causes diminished accessibly confined to areas such as West, North, and mainland Vancouver, Burnaby, Richmond and Delta. Figure 6(c) shows that over time, changes to the urban 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. Finally, the loss of the Oak Street Bridge, as illustrated in Figure 7 appears to affect Richmond and Delta most severely, while parts of Mainland Vancouver, Burnaby, and North Vancouver experience improvements in accessibility over time.

Overall, based on these likely damage scenarios, risk to the region's transportation system increases over time. The only exception, however, is the Lions Gate Bridge damage scenario. It would appear that the principle reason for these changes in risk is due to expected changes in bridge utilization over time. For instance, 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 0.15%. Reduced usage of this bridge, would place less of a burden on future transportation systems, and is why accessibility over time improves. Conversely, the largest reduction in accessibility was seen for the Alex Fraser Bridge damage scenario. This is a direct result of a 7.36% increase in bridge utilization. This increase in usage would put greater burden on surrounding road links, and thus would cause reductions in accessibility over time. Lastly, the Oak Street damage scenario would produce an overall reduction in accessibility for the region. This is the result of a 4.02% increase in utilization for the Oak Street Bridge.

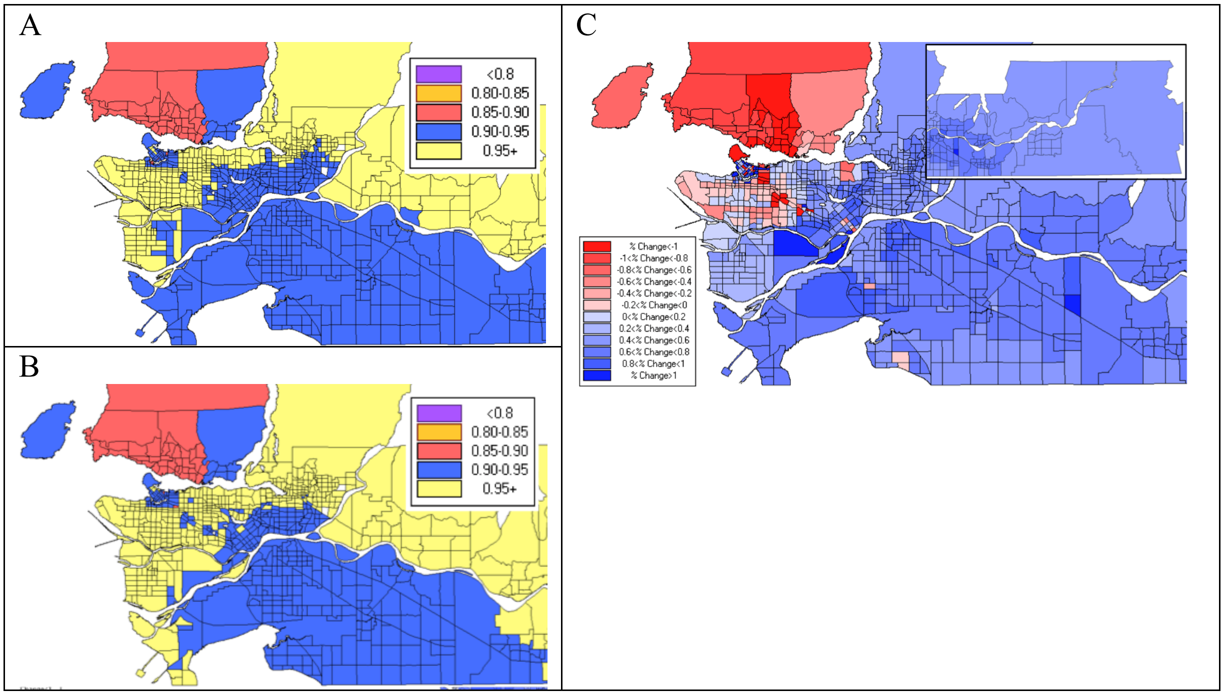

Figure 5. Lions Gate Damage Scenario (a) 2004 Accessibility, (b) 2021 Accessibility (c) Percent Change in Accessibility

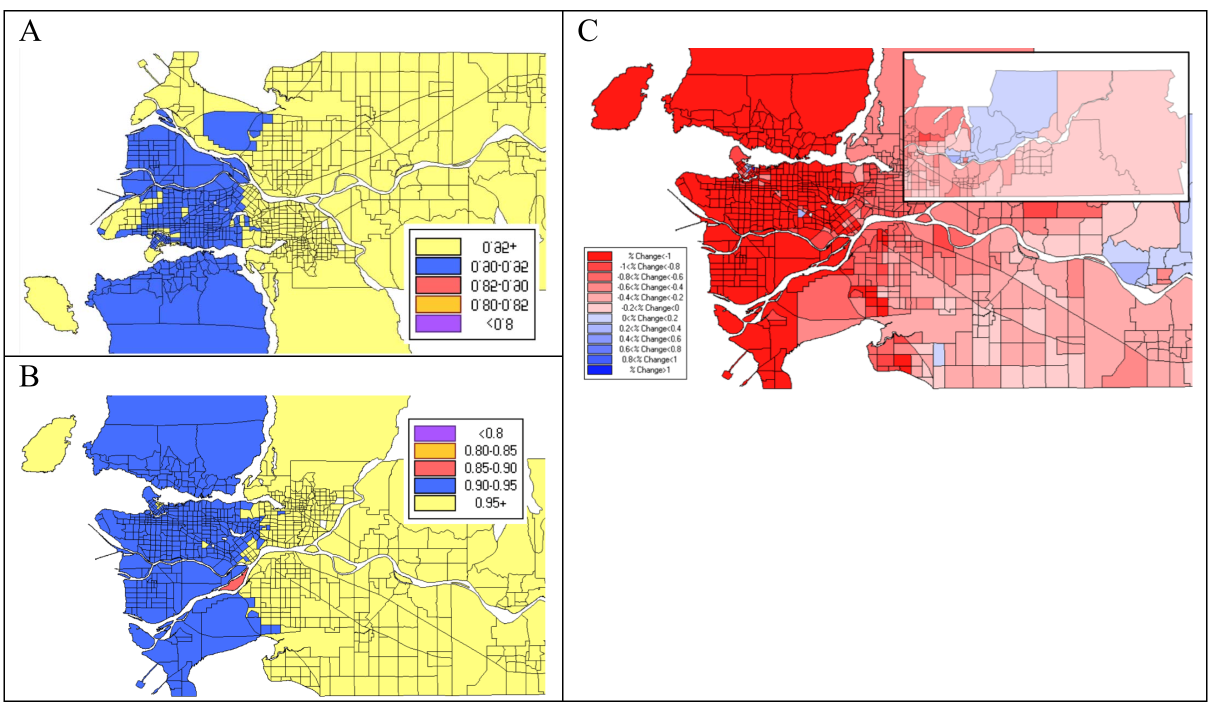

Figure 6. Alex Fraser Damage Scenario (a) 2004 Accessibility, (b) 2021 Accessibility (c) Percent Change in Accessibility

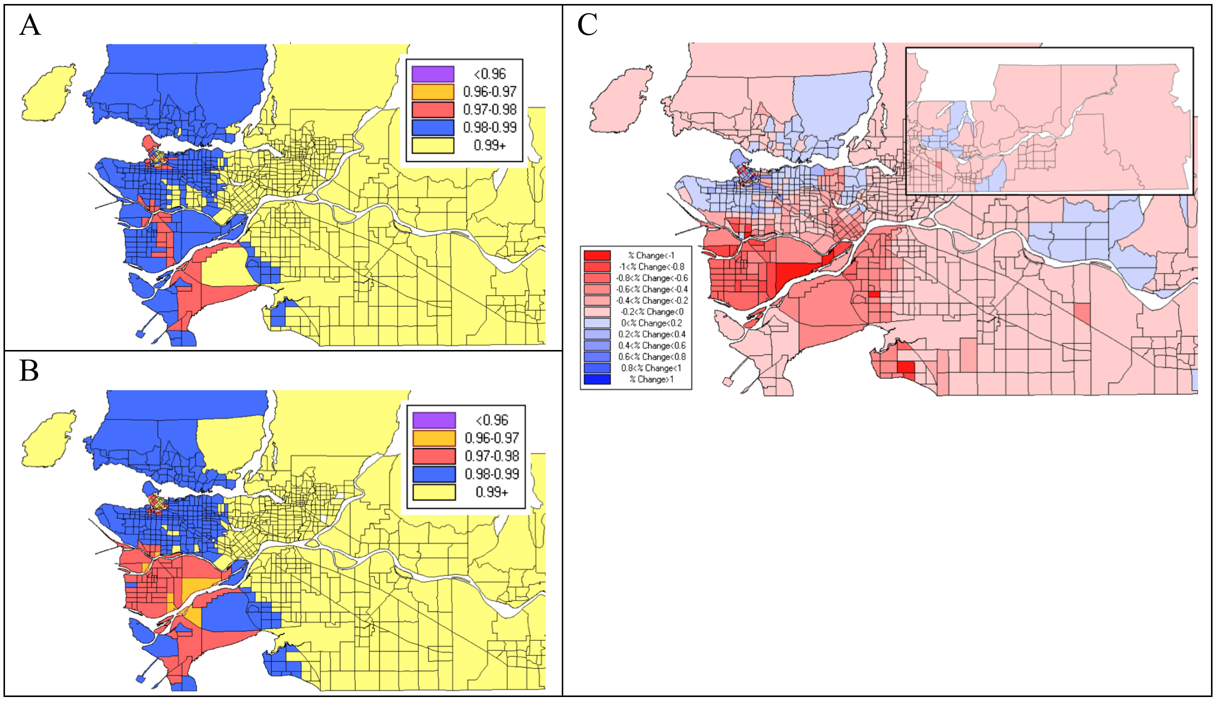

Figure 7. Oak Street Damage Scenario: (a) 2004 Accessibility, (b) 2021 Accessibility (c) Percent Change in Accessibility

4. Conclusion

Overall this research has attempted to develop a methodology for assessing post-earthquake transportation performance using the newly developed *Rt* software. In the process of developing a methodology, it has also determined probable post-earthquake damage scenarios, and how transportation systems in Metro Vancouver will perform. Overall, the 10 bridges under examination appear to be able to withstand most of the force produced by various earthquakes under a circular area source. However, among the most likely damage scenarios, transportation risk in many instances appears to increase over time. As a direct consequence of changes in bridge utilization, transportation performance for the most part, diminishes. In sum, this research can aid decision-makers by providing them with information related to retrofit prioritization or appropriate post-earthquake repair strategies. Furthermore, this research can aid urban planners in choosing land-use configurations which would minimize long-term transportation risk.

Acknowledgements

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