LIFELINE NETWORK RESILIENCY AND RECOVERY FOR EMERGENCY RESPONSE PHASE 1

Type of Report

PROJECT ###

LIFELINE NETWORK RESILIENCY AND RECOVERY FOR EMERGENCY RESPONSE PHASE 1

Type of Report

PROJECT ###

By
Oregon State University
College of Engineering: Civil and Construction Engineering Department
101 Kearney Hall
Corvallis OR 97330

For

Oregon Department of Transportation
Research Section
555 13th Street NE
Salem OR 97301

And

Federal Highway Administration
400 Seventh Street, SW
Washington, DC 20590-0003

SEPTEMBER 2014

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle		5. Report Date -month- -year- 6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No.
9. Performing Organization Name and Address Oregon Department of Transportation Research Unit 200 Hawthorne Ave. SE, Suite B-240 Salem, OR 97301-5192		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Oregon Dept. of Transportation Research Section and Federal Highway Admin. 555 13th Street NE 400 Seventh Street, SW Salem, OR 97301 Washington, DC 20590-0003		13. Type of Report and Period Covered _______ Report 14. Sponsoring Agency Code
15. Supplementary Notes		
16. Abstract		
17. Key Words	18. Distribution Statement Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages / 22. Price

Technical Report Form DOT F 1700.7 (8-72) Reproduction of completed page authorized Printed on recycled paper

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

DISCLAIMER

Table of Contents

1.0 INTRODUCTION

1.1 MOTIVATION

The last Cascadia Subduction Zone event was in 1700's which resulted in a 9.0 magnitude earthquake. This type of event can cause severe damage to the built environment. Recent disastrous events such as the 2011 Japan earthquake have raised questions for the state of Oregon's emergency preparedness. The transportation network is a key component of the recovery efforts and the current 'health' of the network will be analyzed. The goal of this research is to take a proactive approach to emergency response and to identify alternative local roads that can be utilized in recovery efforts.

Historically, evacuation and recovery efforts have been responsive to an event. The warning of a storm prompts evacuation orders then, after the storm planners develop recovery plans based on post-storm conditions. By designing or building-up the existing infrastructure to be resilient to disastrous events before an event occurs the evacuation time, damage, deaths and recovery time can be minimized. CH2MHill has determined a system of lifeline routes for Oregon, but only includes state highways. This research aims to include local roads into the system of lifeline routes. This could also help planners prioritize improvement projects to minimize the impact to the transportation network.

This project will focus on the post-disaster Portland area. Portland is the most populated area in Oregon and is home to thousands of businesses. The quick recovery of Portland is key since it is a huge part of Oregon's economy.

1.2 STAKEHOLDERS

- Oregon Department of Transportation (ODOT)
- Portland General Electric (PGE)
- NW Natural Gas
- Port of Portland
- Bonneville Power Administration (BPA)
- Eugene Water & Electric Board (EWEB)
- Tualatin Valley Water District
- Portland Water Bureau

1.3 PROJECT OBJECTIVE

Identify major arterial local roads in Portland, Oregon that can be utilized in recovery efforts after a disastrous event (i.e. an earthquake) if major interstate or state highways are unavailable in order to minimize the rescue and recovery time. This will contribute to evaluating the overall resiliency of the transportation network in Portland as well as consideration of our stakeholders.

1.4 OREGON'S EARTHQUAKE HISTORY

There is no historical record (past 150 years) of a subduction zone earthquake, but there have been lower magnitude earthquakes. As reported on May 28, 2014 there was 1 earthquake day of, 5 earthquakes in the past 5 days, 25 earthquakes in the past month, 285 earthquakes in the past year, however all of the earthquakes were between 1.5 – 2.5 magnitude earthquake (USGS, 2014). Figure 1 shows the locations of the recent earthquakes.

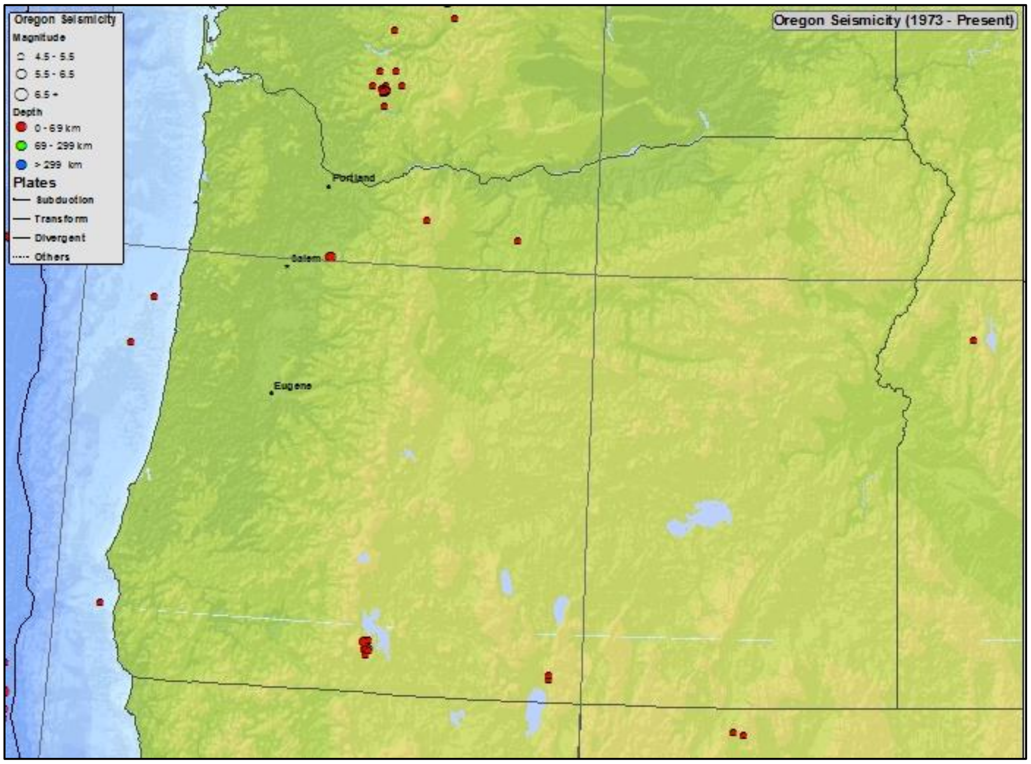

Figure 1: Oregon Recent Earthquake Locations –Source (USGS, 2014)

If there were to be a 9.0 earthquake, which is the expected magnitude of a Cascadia Subduction Zone event, it is predicted that I5, US26, and I84 would be impassible (Neves, 2011).
A Portland State University (PSU) is conducting research to test the seismic vulnerability of Portland's bridges. Generally, most of the bridges are vulnerable from some damage to full collapse based on a simulation of a 9.0 earthquake. The Ross Island Bridge, Broadway Bridge and Steel bridge are predicted to be unusable after a 9.0 earthquake, while Fremont and Burnside remain uncertain. Burnside has been seismically retrofitted in 2002, but only ensure that the bridge deck will stay connected with the columns, usability after an earthquake is uncertain. The safest bridge is the Marquam Bridge which has been seismically braced to endure a Cascadia Subduction Zone event. PSU identifies awareness as the first issues followed by testing and then funding (Showman, 2013).

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Resiliency aims to ensure that a system is minimally impacted by an outside source, such as a natural disaster, through a proactive approach. Historically evacuation and recovery efforts have been responsive to an event. The warning of a storm prompts evacuation orders then after the storm planners develop recovery plans based on post-storm conditions. By designing or developing the existing infrastructure to be resilient to disastrous events before an event occurs the evacuation time, damage, deaths and recovery time will be minimized. CH2MHill has determined a system of lifeline routes for Oregon, but only includes State Highways. This research aims to include local roads into the system of lifeline routes that will meet all of the goals above.

2.2 EVACUATION

How to use non-state routes (not maintained by state) such as local routes to evacuate? What are time-minimizing evacuation strategies?

Thoroughly developed evacuation strategies before an event occurs can significantly reduce evacuation time which can increase the number of survivors. Chiu et. al,. (2008) explored contra-flow and phased evacuations strategies on a regional scale. They developed a mesoscopic vehicular traffic simulation model in which individual vehicles are given individual characteristics that follow a speed-density relationship and can respond to dynamic traffic conditions. The Houston-Galveston hurricane was investigated to demonstrate the abilities of the model. The entire street network of the Houston Metropolitan area were used while only the primary and secondary highways of the surrounding area were used. The study revealed that contra-flow improved the travel time but did not completely eliminate congestion in high risk zones. It was recommended that contra-flow along with phase evacuation be used in high risk zones.

Montz et al., (2013) also explores the idea of using a combination of evacuation strategies based on the characteristics of a particular threat. He proposes a flexible response plan to optimize desired results. Models were used to test different hurricane scenarios. A base plan was developed, then the plan was altered based on the storm conditions (open/close major routes, implement contra-flow). Simple alterations resulted in time and fuel-cost savings. The author acknowledges that the key limitation is communication of the plan to evacuees. It is already difficult to relay static evacuation plans to evacuees, but flexible or dynamic plans will be even trickier to convey. This study also was limited to vehicle evacuation along major routes. Montz mentioned the use of local roads during evacuation but concluded that it may extend the travel time as opposed to interstate evacuation. The goal of our research is to identify local roads that can be used during an evacuation to provide alternative routes in the event that access to a state highway is blocked. Interstate evacuation is ideal, but it cannot be the only means of evacuation.

Miller-Hooks & Krauthammer, (2006) introduces a computer-based expert decision support system to aid emergency responders and evacuees in rescue efforts. This system utilizes sensor technology to provide real-time assessment of a building along with on-line optimization techniques that provide recommended evacuation instructions. This system increases the response time to an emergency situation providing real-time assessment and evacuation instructions for evolving conditions. The communication of the recommended evacuation instructions relies on electrical power which can't be guaranteed after such event. Miller-Hooks suggest implementing redundancy to guarantee that both the sensor and communication equipment can operate in extreme conditions. Alternative measures of communication should be explored in the event that all power is lost. As state above, communication is a key problem during emergency evacuations (Montz et al., 2013). A reliable method of communication between evacuees, the rescue team and planners needs to be developed. This type of computer-based decision system could be utilized to determine the optimal routes to transport resources.

An efficiently planned evacuation can save many lives. However, what are the actual behavior patterns of evacuees and how do they respond to emergency evacuation warnings/instructions? Dow & Cutter, (2002) investigated the effect of household decisions on the increased demand on transportation infrastructure during evacuations. Evacuation models were developed to simulate evacuation scenarios; however key assumptions such as the number of cars per household are incorporated. Dow and Cutter, (2002) study aims to examine the accuracy of these assumptions utilizing Hurricane Floyd and South Carolina. Telephone surveys were conducted which included questions on the topics of the number of cars taken, destination, choice of route and reasons for leaving. It was found that 65% of the people evacuated, 25 % of the people that evacuated took more than one car, and there was a major preference for interstate routes. Evacuees will select congested interstate routes over rural routes in fear of being isolated or losing wireless connection as well as assurance of services along the interstate. In estimating resiliency in the transportation network such as identifying alternative non-state routes, it is important to consider the likelihood of evacuees actually using those options. Hurricane Floyd evacuee behavior suggests that although there were alternative rural routes, most evacuees stayed on the congested interstate. The proposed resiliency-based framework will provide evacuees with confidence to selecting non-state, lifeline routes. This will hopefully alleviate the congestion on state highways and reduce evacuation times.

Chiu et al., (2008) investigated evacuation strategies on a large-scale. Inclusion of local roads in the evacuation model could further reduce evacuation times. Ozbay et al., (2012) developed a framework to utilize existing regional transportation models, which include local roads, with some modifications as an evacuation plan model for a variety of threats (i.e. hurricane, a toxic chemical leak, dirty bombs, and nuclear event). The framework includes determining the evacuation region, preparation of evacuation trip tables, transportation network adjustments, selecting an appropriate evacuation model and analyzing the model output. Ozbay et al., (2012) implements the proposed framework with a case study, evacuation of northern New Jersey, for the various threats. The results indicate that regional planning models are suitable for evacuation modeling and analysis. There were some issues with the different assumptions since they are location specific. However, regional transportation models include local roads and can be a good starting point.

2.3 RESOURCE ALLOCATION

How to route drinking water, power, and movement of people on the partially damaged road network to minimize the overall recovery time from the disaster?

Evacuation is only the first step in natural disaster preparation. What happens after the storm? There have been many studies that have developed a framework or strategy to minimize recovery time and maximize available resources. Research efforts have focused on reconstruction strategies, efficient resource distribution systems and accessibility on a damaged network. Sánchez-Silva et al., (2005) and Horner and Widener, (2011) focused on accessibility on a damaged network. Sánchez-Silva et al., (2005) present a model for optimizing assignment of resources based on the probabilistic reliability of the transport network. The proposed methodology utilizes Markov chain modeling of failure states and estimates of expected cost and accessibility to optimize resource allocation. The expected cost is dependent upon both the state of infrastructure and user decisions. Accessibility is dependent on cost which implies that increases in cost for a route result in decreases in accessibility. Optimization of resource allocation is investigated on the improvement of accessibility for one route and also for the network as a whole. A case study in Columbia is used to illustrate the applicability and the benefits of the model. The results show that improvements to the failure rates and focusing on improvements of individual routes yields higher accessibility. This study identifies the optimum allocation of resources for road maintenance and rehabilitation, however one must make several assumptions for the model.

Horner and Widener, (2011) investigate the effect of hurricane disaster on the transportation network related to relief distribution center location. He focuses on the impact of uncertainty by simulating different hurricane scenarios and measuring accessibility throughout the transportation network. This study is motivated by the portion of the population that does not evacuate to safety before a disastrous event such as a hurricane. Basic necessities such as food, water and ice still need to be made available to those people who remain behind. A model was developed to minimize the distance between population locations and relief distribution facilities. Uncertainty enters the study through the application of generic and random roadway failure. Each scenario a specified percentage of the links are randomly selected and deemed inaccessible. Once the failure links are determined the shortest distance from a population zone to a potential relief distribution location is calculated. This process is repeated to assess the impact on the network. The aim of the study was not to identify an optimal location for relief distribution centers, but rather assess the impacts of uncertain outcomes. The model was able to identify potential locations that were accessible in all scenarios and other locations that are robust in most scenarios. The main takeaway from this study is that transportation networks are dynamic and cannot be assumed to fully serve the population after a disastrous event, thus planners need to consider the event of network failures. One drawback is the identification of bridge locations. Bridges tend to be more vulnerable in a natural disaster and often times are the only link. Special consideration for bridges is necessary if present. The proposed framework considers bridges and overpasses in the roadway failure selection as opposed to a random selection.

Wallied Orabi et al., (2009) focused on reconstruction strategies. The authors develop a robust recovery planning model for damaged transportation networks considering the availability of limited resources after a disaster. The model begins by identifying possible solutions to satisfy the decision variables (project priorities, project assignment and overtime policy). The recovery schedule, performance loss and reconstruction cost are used to rank each solution. The process is iterative, to account for the dynamic nature of recovery efforts, until an optimal set of solutions is identified. Each solution will have cost-time tradeoffs in which decision makers can evaluated based on the specific requirements of the recovery efforts. This paper identifies the resource allocation of reconstruction resources for a damage transportation network. Transportation is a key network in the recovery process, once the road network has recovered other resources such as food and water will be able to enter the devastated area. Timely reconstruction of a damaged transportation network can significantly reduce the recovery time by adding alternative routes.

Tzeng et al., (2007) and Orabi, (2011) concentrate their efforts on developing efficient resource distribution systems. Tzeng et al., (2007) developed a system to distribute relief material effectively and fairly. The fuzzy multi-objective programming model was used to design a relief delivery system focusing on minimizing cost, minimizing travel time and maximizing satisfaction. The model includes identification of key assumptions, pre-disaster evaluation of area, post-disaster data collection such as extent of road destruction, estimation of commodity demand, identification of collection and transfer depots and finally implementation of GIS software to calculated the quickest route. Taiwan's earthquake in 1999 was used as a case study and the results provide insights for the decision support system. This method provides a means of routing commodities along a partially damaged transportation network.

Orabi, (2011) proposes a web-based resource management system that will provide up-to-date information between the suppliers, contractors, state department of transportation, and the public. The goal is to provide a medium of communication between stakeholders during recovery efforts after a natural disaster. Each can be accessed via the internet and alerts can be sent by email or text messages. The proposed resource management system can help to improve current disaster management practices and minimize the impacts of the disaster. Again, electrical power cannot be guaranteed thus an alternative plan to track and allocate resources is needed. Building in redundancy into the ground network can help to alleviate some of the issues such as communicating information after an event.

2.4 RESILIENCY

How to identify the most vulnerable links/segments on the partially active network? How to measure resiliency?

There are many studies that have developed frameworks to measure the resiliency of a network. Travel time, distance, volume change, bridge locations and unique local factors have all been suggested as a means to quantify resiliency. The capability of a network to bounce back to pre-storm conditions in a timely manner is important. The main objective of Pant's, (2012) study is to minimize the time between the breakdown and the completion of the recovery stage. Pant, (2012) presents a 4-step framework to evaluate the resiliency of the transportation network. The first step is normality, checking the network functioning under normal conditions. The second step is the breakdown in which disruptions occur within the system in order to investigate how the network reacts to the disturbance. The third stage is self-annealing where the network users select alternative routes. Finally the last stage is the recovery where damages are repaired and the facilities are restored to 'normal' conditions.

On the other hand Freckleton et al., (2012) take a proactive approach. The main objective is to identify the weaknesses in the transportation network in order to prioritize improvement projects before an event occurs. He evaluates the resiliency of transportation networks based on four core metric groups each containing equal-weighted attributes with ranges of measurements relating to low or high resilience. A sensitivity analysis, changing one weakness to determine which variable has the greatest impact, is conducted to prioritize improvement projects. Freckleton et al., (2012) successfully identified and prioritized improvements to increase the resiliency of the Salt Lake City, Utah transportation network. The types of attributes included in his investigation were excellent including availability of alternative routes, goods and material access, and emergency response. However, the data is condensed into comparable values such as number of locations per area which may not be fully representative of the reality. It does not take into account where these facilities are actually located. For example, the goods and materials may be concentrated in one section of the area, leaving the distant sections vulnerable. The proactive approach is noteworthy, but inclusion of a spatial analysis, mapping out the resources to identify the vulnerable areas, would be beneficial by aiding decision makers in allocating resources.

Adams et al., (2010) presented a method to evaluate the resilience ratings of road corridor segments. The metrics for resilience include alternate route distance, alternate route travel time, change in traffic volumes on the alternate routes, and the change in traffic level of service. ArcGIS was used to identify alternate routes in the corridor. They calculated a vulnerability rating of road segments and existing structures on the road segments in form of a Risk Priority Number (RPN) on a scale with values ranging from 1 to 10 using the failure mode and effects analysis (FMEA) method for hydrologic, overloading, and weather related modes of failure. Finally, resilience rating of road corridor segments was determined using the RPN, the economic importance of segments and metrics for evaluation of resilience based on alternate routes.

Frangopol and Bocchini, (2011) focuses his resiliency assessment on bridge rehabilitation interventions because bridges were determined to be the most vulnerable component of the transportation network. Post-earthquake recovery efforts are addressed with a bi-objective optimization framework. The first objective is to maximize the network resilience over the investigated time horizon and the second objective is to minimize rehabilitation cost. A multi-objective genetic algorithm is used to evaluate a bridge network located in the Lehigh Valley. It can automatically identify the bridges that need to be rehabilitated first and the optimal damage recovery rates in order to quickly restore the original network functionality. One advantage of this method is it extends the applicability to complex transportation networks.

Leu, (2010) introduces a GPS-based approach for estimating the resiliency of ground transportation networks and aims to validate the framework through a case study on Melbourne. The framework includes gathering GPS data, modifying the data, conducting a resilience assessment, analyzing the results and finally making reasonable conclusions. GPS data is used to build networks, the traditional definition of a node is changed, and the resilience assessment utilizes structural measures to calculate loss of connectivity and the effect of distance gaps. The resilience assessment identifies the vulnerable areas to analyze which highlight the underlying issues of the low resiliency in the network including lack of redundancy, low alternative routes and existence of bottlenecks. This framework provides a low-cost, versatile method that can be easily adopted for any area covered by a GPS map. As acknowledged by the authors other analysis tools and visualization of the spatial vulnerabilities could be included in the model to generate a more comprehensive assessment.

Tamvakis & Xenidis, (2013) summarizes previously proposed methods for quantifying resilience and suggest a framework that provides an effective and comprehensive measure of resiliency. The paper discusses the strengths and weaknesses of previous methods, then highlights the collective problems, and finally presents a method that solves all the identified problems. The issues with current methods include 1) indirectly measuring resilience, 2) utilizing tools not well-fitted to resiliency, 3) difficulty integrating different aspects such as technical and organization, 4) lack of comprehensive measure of resiliency, but rather quantification of individual properties of resilience and 5) some methods are case dependent which limits application. Entropy theory could overcome many of the weaknesses listed above. *Resilience is a system's property that describes the system's capacity to confront the effects of a disruptive event and recover to a predefined performance/quality level. Entropy is also a system's property that describes the level of a system's disorder due to an internal or external cause.* Entropy can be directly measured and has been applied to multiple disciplines such as engineering, economics, and anthropology. Total entropy of a system can be represented by the sum of individual entropies. Entropy can also be statistically assessed which can provide researchers with confidence. This paper simply suggests the use of entropy theory to measure resilience, but the application to a case study is required to provide proof of concept. Future work is required to implement this framework and develop a methodology to determine resilience utilizing entropy.

Kiremidjian et al., (2007) present a method to evaluate the total cost associated with damage to bridges and travel time delays of a transportation network due to a seismic event. This paper aims to enhance and combine previous methodologies used to estimate loss by integrating local site conditions into the risk assessment such as effects of ground shaking and probability of liquefaction or a landslide at bridge locations. The enhanced methodology includes identification of the hazard and its impacts, collection of network inventory, analysis of the transportation network in GIS, determination of physical damage and travel time delays and finally estimates the repair cost and operational loss. Liquefaction was found to cause the greatest loss. However, not only are the effects of different hazards region dependent, the assumptions to damage costs are also region dependent. The analysis procedures to identify vulnerable areas could be mimicked in our resiliency analysis. This study utilized GIS to overlay the transportation network over susceptibility maps to identify potential failure locations. This process could be used to identify the vulnerable links on non-state routes.

Frazier et al., (2013) aims to determine the baseline resilience of a community. Unlike previous models Frazier includes differential weighting and spatial and temporal elements to determine place-specific resilience indicators. Frazier et al., (2013) believes that identifying unique local factors will enhance the effectiveness of resource allocations, hazard mitigation and community preparedness. The proposed framework reviews county/community disaster plans, conducts a focus group with city and county representatives, and implements a spatial analysis. The method provides more accurate resilience levels at the community scale and identifies community specific problems. This will help decision makers prioritize projects and aid in distributing limited resources. Although place specific or unique community problem identification is important, it is just as important to look at the network as a whole. For example, Dow and Cutter, (2002) investigated the evacuation issues of Hurricane Floyd in 1999. Hurricane Floyd affected multiple states (Florida, Georgia, and South Carolina), thus the evacuees from the southern states met the evacuees of the northern states creating congestion on the interstate. Once the community problems are identified it is important to examine the impacts on adjacent communities.

3.0 METHODOLOGY

3.1 FRAMEWORK

The PTV VISUM software was utilized to analyze the traffic operations of the Portland network, provided by Portland Metro, under stressed conditions. The purpose of this research is to evaluate the network performance after a disaster and to identify local roadways that can be used as a lifeline route for people evacuating from the disaster area as well as during the recovery efforts. Various tools and attributes such as the shortest path search or volume comparison in VISUM will help to identify vulnerable links in the network. The capacity of the vulnerable links will be reduced to zero to simulate inaccessibility which will allow the traffic to redistribute onto the local roads highlighting alternative routes. Pinpointing alternative routes has the potential to decrease evacuation and recovery time. The procedure sequence is summarized in Figure 2 on the next page followed by a brief description.

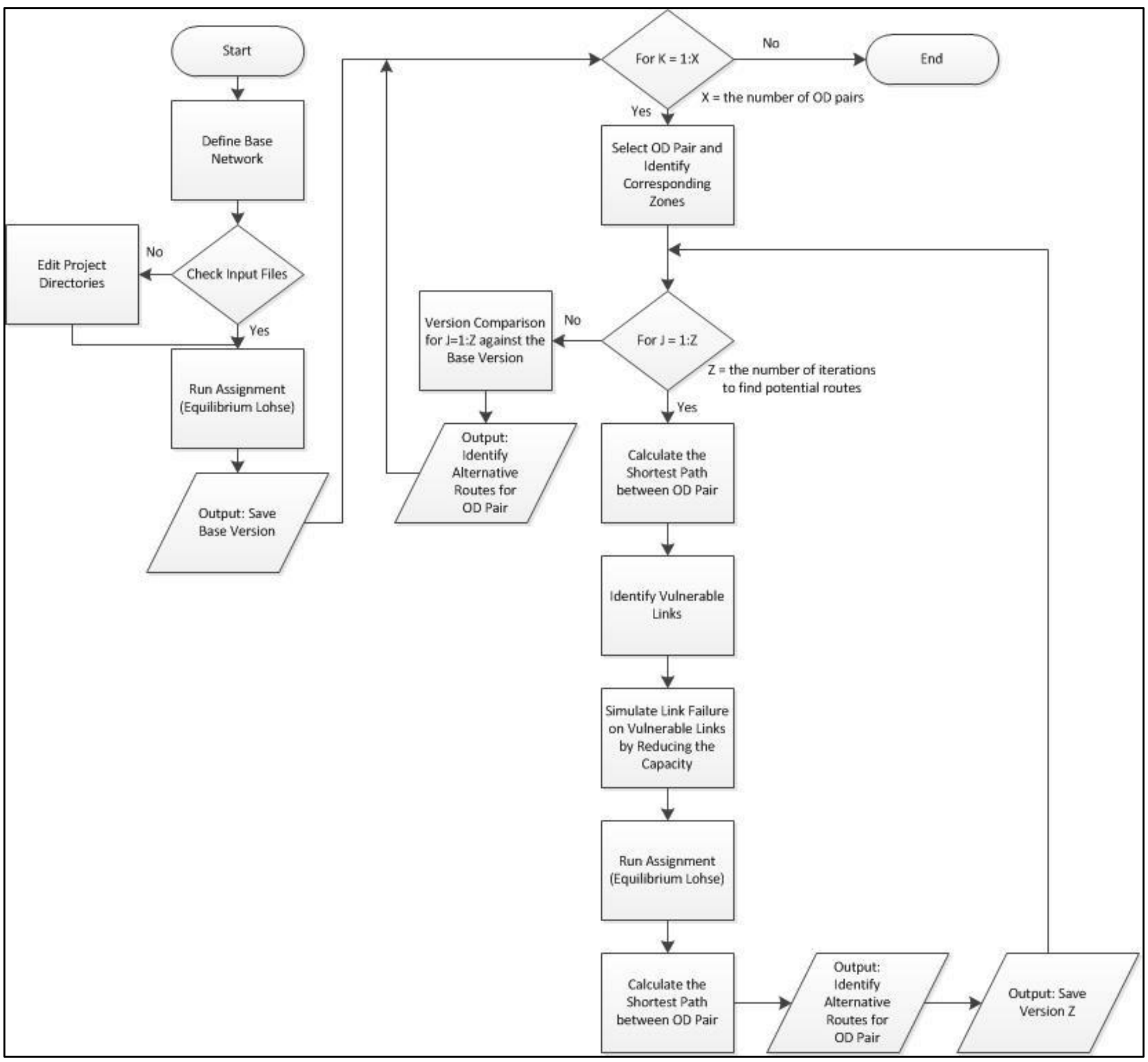

Figure 2: Framework to Identify Alternative Routes in VISUM

1. Define a Base Network
    a. Establish a base/control network in order to assess the impact of the network modifications for the different scenarios that will be investigated. Each scenario will vary by capacity restraints and be compared to the base version. In our case, the base network was provided by Portland Metro. The network included all roads in the Portland region classified as collector roads and above yielding 12,532 nodes, 32,010 links and 2,162 zones.
2. Check Input Files
    a. This step ensures that the network is complete and the correct demand data is loaded based on the desired time period. In our case, the afternoon peak period ,5-6 pm, demand data was utilized.
3. Run Assignment
    a. Equilibrium Lohse static assignment utilizes an all or nothing approach, meaning that it assumes all of the traffic will take the shortest path based on time between a specified origin and destination (Friedrich, 2008). Each user minimizes their travel time without consideration to surrounding users. This assignment stores information gained from previous trips for the next route selection. The learning process produces more reasonable routes and distributes the traffic realistically. (Ag, n.d.)
    b. From the PTV VISUM User Manual and Procedure Sequence. The maximum number of iterations is 40. The route volumes are calculated according to the method of successive averages which ensures a safe but slow convergence. The Heuristic rule is utilized to smooth the estimate impedance.
4. Output: Save Results (Base Version)
5. Identify a Origin Destination (OD) Pair and Corresponding Zones
    a. Determine the OD pairs you would like to investigate. For example, the analysis evaluates the connectivity between ODOT and the Portland International Airport (PDX). Once the OD pair was identified the corresponding zones were determined (zone 26 and zone 139, respectively).
6. Identify the shortest path
    a. In VISUM the shortest path can be determined based on time, distance, impedance or a user-defined attribute. The in-vehicle time in the loaded network was utilized in this analysis.
    b. The input version is the previous version. We want to piggy back on the failures in order to develop the worst case scenario. If plan A (shortest path from base version) doesn't work what is plan B and so on. How does the traffic redistribute? What other local roads can be used?
7. Identify Vulnerable links
    a. Identify vulnerable links along the shortest path that are susceptible to earthquakes. This selection process mainly focused on links with a bridge or overpass.
8. Reduce the Capacity of the Vulnerable Links
    a. In order to simulate a failure the capacity of the vulnerable link along with other affected links were set to zero.
9. Re-run assignments

    a. Equilibrium Lohse Assignment
10. Re-calculate the New Shortest Path with the Capacity Modifications.
    a. This new shortest path will highlight potential alternative routes that could be utilized during evacuation or recovery efforts.
11. Identify alternative routes
    a. Alternative routes can be identified based on the shortest path, version comparison and accessibility analysis. The shortest path provides a platform to evaluate the performance of the network under different stress conditions or capacity restraints. As the network capacity is modified throughout the different scenarios, the shortest path shifts onto different roadways which are then deemed a potential alternative route. The version comparison and accessibility analysis provide additional information on the performance of that link/roadway.
12. Save results (version z)
    a. Save the version under a different name with the capacity changes. This version then becomes the input to find the next shortest path. Steps 5-10 are repeated until all possible routes are discovered. This is an iterative process. For a single OD pair the different scenarios build on top of one another until the worst case scenario is reached.
13. Version comparison/Accessibility Analysis
    a. The version comparison tool in VISUM allows comparison of any attribute from any network object between two networks. Compare all the versions created in steps 5-10 to the base version. Version comparison allows a deeper investigation into the different scenarios. The traffic (re)distribution can be compared. The accessibility analysis tool in VISUM allows the user to estimate the connectivity and travel time from one point to another.

3.2 SCENARIO DEVELOPMENT

3.2.1 OD Pair Selection

In order to demonstrate the proposed framework, a few origin-destination (OD) pairs were established. The Portland International Airport (PDX) is a major hub for the distribution of goods and services. For example, emergency supplies and services could be circulated through the airport. Two stakeholder locations, Oregon Department of Transportation's (ODOT) and Bonneville Power Administration's (BPA) offices in Portland, were utilized in the analysis. ODOT resides on the west side of the Willamette River while BPA is located on the east side, as shown in **Error! Reference source not found.**. These two locations were selected to demonstrate the accessibility of PDX from either side of the river so that companies not included in the analysis can get a rough idea of their potential connection to PDX.

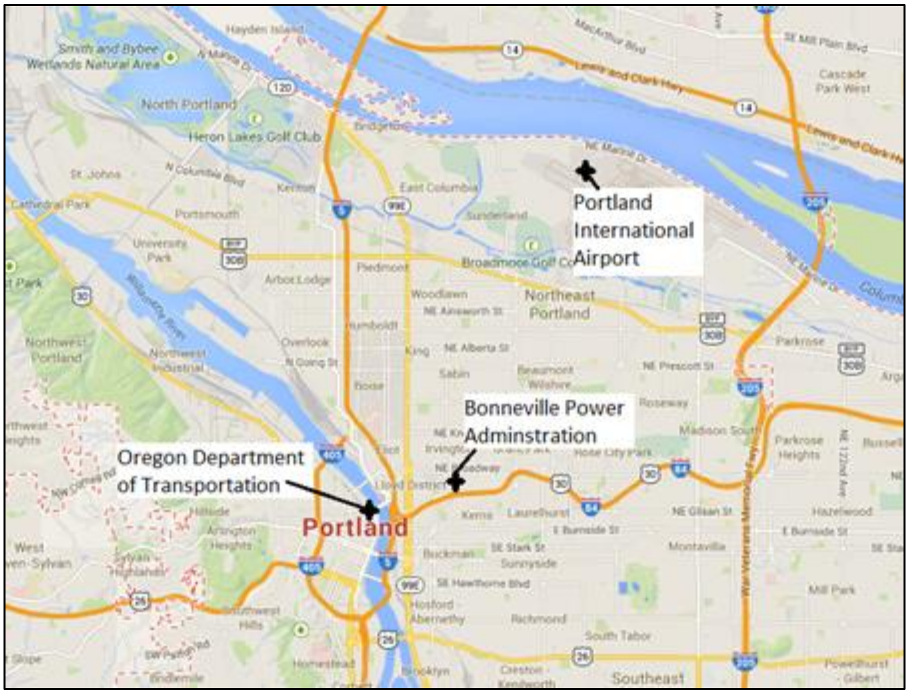

Figure 3: Location of Selected Stakeholders for the Resiliency Analysis – Source (Google Maps)

3.2.2 Vulnerable Links

The development of scenarios for each OD pair came as a natural by-product of the shortest path analysis. The shortest path is based on shortest travel time. Vulnerable links or roadway sections along the shortest path based were identified based on the presence of a bridge or overpass. These types of roadway segments are highly susceptible to failure in the event of an earthquake. Bridges are of particular concern because the Willamette River travels through Portland dividing the area in two. Overpasses should also be considered because during an earthquake an overpass could fall onto the major thruways of the region and interfere with emergency response vehicle transport, as shown in Figure 4.

Figure 4: Overpass Failure in California after the 1994 Northbridge Earthquake (6.7 Mw) - Source (Univeristy of California Los Angelos, n.d.)

The data of construction is also an important aspect to consider. The Bridge and Engineering Section of ODOT developed a Seismic Vulnerability of Oregon State Highway Bridges in November 2009(Oregon Department of Transportation, 2009). ODOT reports that prior to 1958 seismic loading was not typically considered. Between 1958 and 1974 a seismic load of 2% to 6% of the structural weight was used then between 1975 and 1990 the seismic load was increase to 8% to 12% of the structural weight. Earthquakes along the pacific border as well as discover of previously large subduction zone earthquakes prompted ODOT to higher their seismic standard. In 1990 the AASHTO Seismic Design Guide was adopted. Infrastructure built before 1975 without any retrofitting has significant structural collapse potential. Infrastructure built between 1975 and 1994 should also be considered as a moderate potential for structural failure (Oregon Department of Transportation, 2009). Currently, the Marquam Bridge (I-5) is the only bridge across the Willamette that has been retrofitted to withstand a 9.0 Mw earthquake (Showman, 2013). The original date of construction as well as a brief description of the bridge structure is presented in **Error! Reference source not found.**.

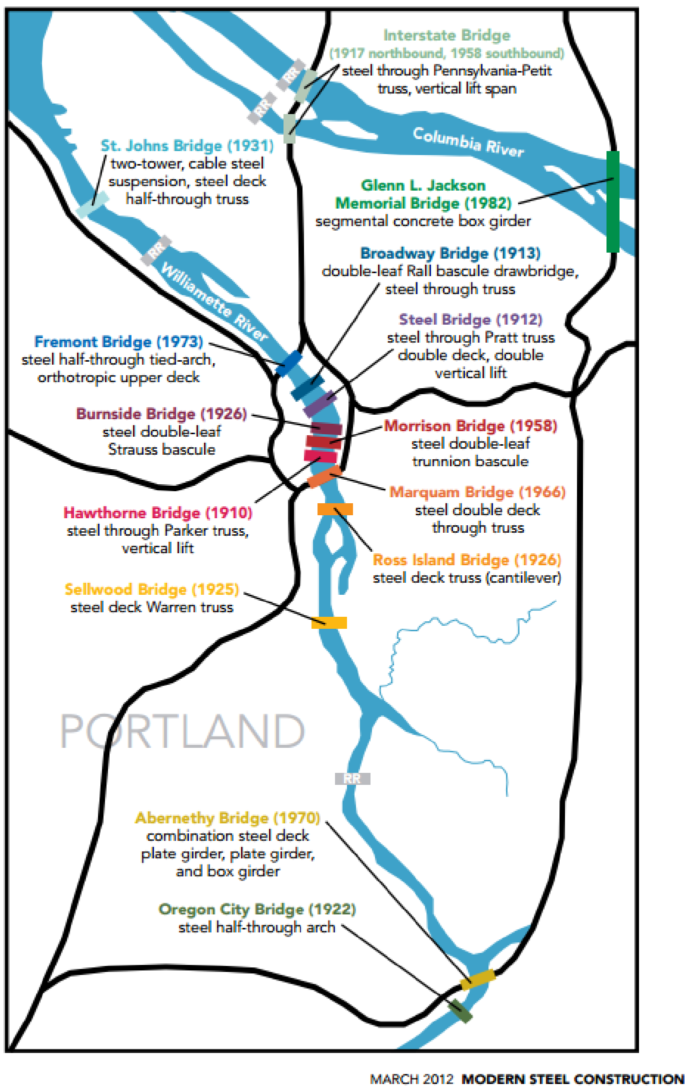

Figure 5: Bridges Located in Portland Oregon – Source (Talbot, 2012)

3.2.3 Identifying Alternative Routes

Once the vulnerable links were identified along the original shortest path, the capacity was set to zero to simulate a failure for those vulnerable links. The traffic assignment was initiated resulting in a new (different) shortest path. The new shortest path highlighted set 'A' of alternative routes that could be used in evacuation or recovery efforts. Then, again the vulnerable links were identified along the new shortest path and replicated as a failure. The traffic assignment and the shortest path search was initiated again yielding set 'B' of alternative routes. This iterative process should be repeated until each set of (useful) alternative routes is discovered.

3.2.3 Version Comparison/Accessibility Analysis

The version comparison tool in VISUM allows the user to compare any attribute in two networks such as volume, volume-capacity ratio, delay time and vehicle miles traveled. After each set of capacities on the vulnerable links are reduced the network is saved under a different name. This allows the user to compare the base or control network to the network under different stressed conditions. The volume of each link of the modified network is compared the volume of each link of the base network. The volume displayed is the difference between the modified network and the base network. Thus a positive volume indicates that there was an increase in volume on that link in the modified network. A negative volume specifies a decrease in the number of vehicles on that link in the modified network.

The accessibility analysis provides additional information about the travel time from one point to another. The connectivity of a point to the entire network is evaluated.

4.0 RESULTS & DISCUSSION

4.1 OREGON DEPARTMENT OF TRANSPORTATION TO PORTLAND INTERNATIONAL AIRPORT

The first OD pair that was investigated was the connectivity of ODOT to PDX. The shortest path based on travel time and volume comparison was utilized to evaluate potential alternative routes traveling from ODOT to PDX.

4.1.1 Shortest Path (travel time)

Base Version:

As mentioned previously, the shortest path is calculated based on travel time. The shortest path travels along Davis St, Steel Bridge, 1st Ave, Multnomah St, Grand Ave, Martin Luther King Jr. Blvd., Lombard St., Columbia Blvd. and 82nd Ave, refer to Figure 6 where the shortest path is highlighted in red. Potential alternative routes include Martin Luther King Jr. Blvd., Lombard St. and Columbia Blvd. The Steel Bridge and sections of Lombard St. have been deemed vulnerable.

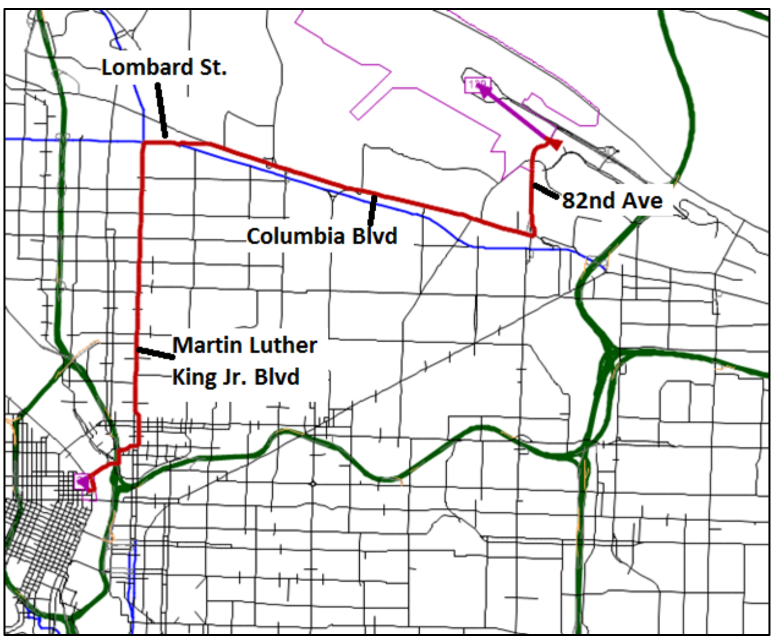

Figure 6: Shortest Path from ODOT to PDX – Base Version

Although there is major uncertainty as to how exactly the roadway will respond to a seismic event, Martin Luther King Jr. Blvd was deemed a potential alternative route because there are no bridges or overpasses along this section of the roadway. Columbia Blvd and Lombard St. could also serve as a potential alternative routes, but along both roadways there is one overpass which could limit the accessibility. The potential failure of the overpass on Columbia Blvd. will be explored in a later scenario.

Lombard St has been identified as a potential alternative route. Lombard St. parallels Columbia Blvd and has two over passes along this section between Martin Luther King Jr. Blvd and 42nd Ave. The section of Lombard St. highlighted in Figure 6 poses no significant threat to connectivity issues, but other portions of the roadway could be vulnerable. Lombard St. also severs as a major connecting roadway from Northwest Portland, specifically Oregon's critical energy infrastructure (CEI) main hub, to the airport (Wang et al., 2012).

Oregon Department of Geology and Mineral Industries conducted an earthquake risk study for Oregon's CEI (Wang et al., 2012). The CEI hub is located in Northeast Portland between the Sauvie Island and the Fremont Bridge covering about 6 miles on the southern side of the Willamette River. The CEI hub houses all of Oregon's major liquid fuel port terminals, liquid fuel transmission pipelines and transfer stations, natural gas transmission pipelines, liquefied natural gas storage facility, high voltage electric substations and transmission lines and electrical substations for local distribution. The Portland International Airport is a large consumer and most of NW Natural's natural gas passes through the CEI hub. The Portland International Airport receives all of their liquid fuels from the CEI hub, thus if the pipeline between the CEI hub and PDX fails, PDX operations will be impacted. Although the liquid fuels travel through a pipeline, Lombard St. (US30B) as well as US 30 are key routes for vehicular access to CEI hub facilities. If these routes are impassible, there may be a delay in reviving PDX operations. (Wang et al., 2012)

Lombard St also overpass the I-5 corridor, as shown in Figure 7. If the interchange between Lombard St. (also known as US 30B) is impassible it greatly reduces the connectivity of a north-south interstate and west-east state highway. This interchange will affect two major state routes. Portland of Portland locations and BPA are located west of this interchange. The I-5 leads across the Columbia River to Washington State. This is an example of an overpass (likely to not have been retrofitted) that will have a significant impact on a major corridor. The repair and reconstruction of an overpass failure will not be trivial. CH2MHill identifies I-5 as the most important transportation corridor in the state with much vulnerability.

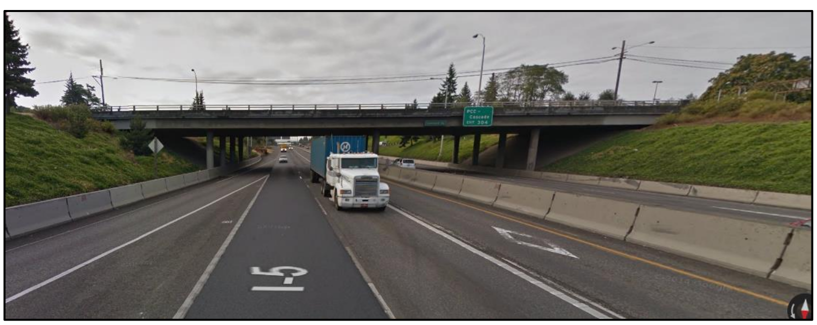

Figure 7: Lombard St Overpass looking Southbound – Source (Google Maps)

The Steel Bridge spans the Willamette River connecting the Lloyd District and Old Town Chinatown. It is a double-deck vertical lift bridge carrying road traffic and light rail on the upper deck while the lower deck carries railroad and bicycle/pedestrian traffic. This multimodal bridge constructed in 1912 plays a key role in the connectivity of US 99W across the Willamette River. It also travels under Interstate-5, hence any damage to the I-5 near any connecting roadways to the bridge could hinder the accessibility. The bridge underwent rehabilitation in 1984-1986 in order to add the light rail line. Given the early rehabilitation date (i.e. before 1994), the bridge should be considered a moderate concern for potential failure. The lower deck of the bridge was also threatened by flooding in three prior years. If the Steel Bridge is impassible it could impact the connectivity of ODOT, Portland Water Bureau, Portland General Electric and BPA. There are utilities that run under the bridge as well as nearby power lines, as shown in Figure 8 . Furthermore, Portland State University's simulation predicts a complete collapse (Showman, 2013). The Steel Bridge was deemed a vulnerable link.

Figure 8: Utilities Under and Near the Steel Bridge – Source (Google Maps)

Version 1:

From the base version the Steel Bridge was identified as a vulnerable link. The capacity was reduced to zero on the Steel Bridge in both directions. The next shortest path travels along Davis St, 3rd Ave, Burnside St, 14th Ave, Sandy Blvd and 82nd Ave, refer to Figure 9 where the shortest path is highlighted in red. Potential alternative routes include Sandy Blvd and 82nd Ave.

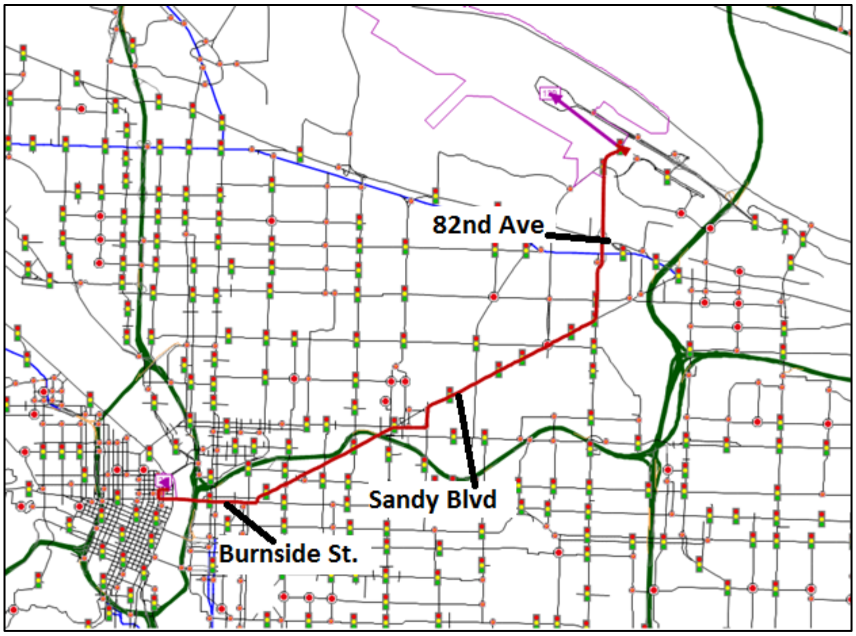

Figure 9: Shortest Path from ODOT to PDX – Version 1

After the capacity of the Steel Bridge is reduced to zero, the next shortest path travels over Burnside Bridge in order to cross the river. The Burnside Bridge is a double-leaf strauss-type bridge spanning the Willamette River (Wikipedia, n.d.). It was built in 1926 and underwent a Phase 1 retrofit in 2002 as reported by Jon Henrichsen, Multnomah County bridge engineer (2012). Phase 1 aims to prevent the structure from failing off its supports during an event to minimize loss of life. Phase 1 doesn't guarantee usability after an event, which is addressed in Phase 2. Henrichsen reports there are no plans for further seismic improvements (i.e. Phase 2) (Henrichsen, 2002). The Burnside Bridge connects I-405 and I-5 providing stakeholder access east and west of the Willamette, refer to Figure 10. It is important to note that the Burnside Bridge was identified as a critical lifeline route as well as the only non-freeway segment in the Regional Emergency Transportation Route for emergency vehicles in 1990s. The average traffic estimated in 2010 is 56,625 with 10% trucks (CityData, n.d.). The Burnside Bridge was identified as a vulnerable link.

Figure 10: Burnside Bridge from West Side – Source (Google Maps)

Sandy Blvd. roughly parallels Interstate-84 and could be an alternative route for drivers traveling east. Sandy Blvd. travels over the I-84 near 37th Ave, as shown in Figure 11. This section of Sandy Blvd. was deemed a vulnerable link because it intersects an interstate roadway and is an overpass. There are also utilities that would be affected with the collapse of the overpass.

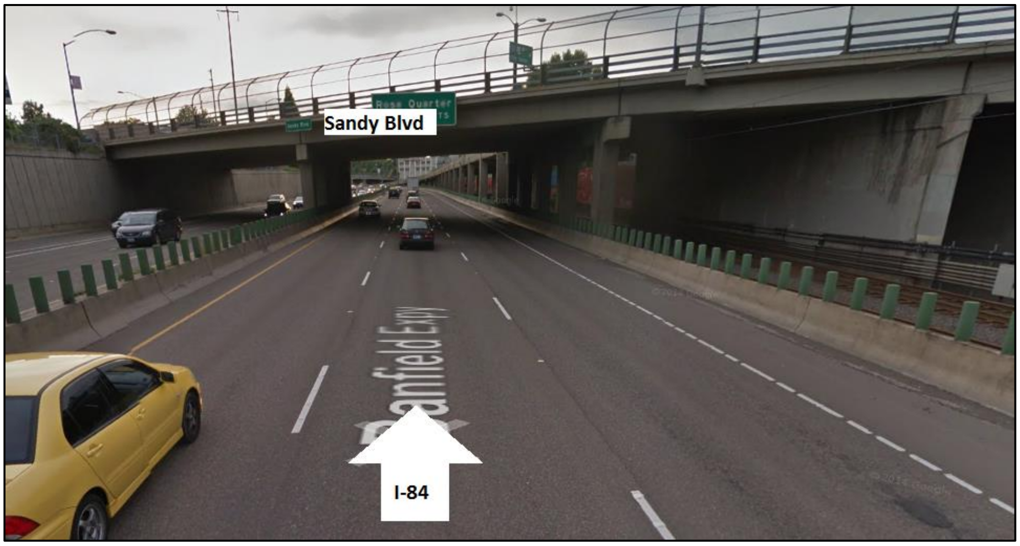

Figure 11: Sandy Blvd. Overpass at I-84 – Source (Google Maps)

82^{nd} Ave. is identified as a potential alternative route. There are some areas along the roadway that are vulnerable, however this roadway has major potential. 82^{nd} Ave runs from north Clackamas County to PDX in north Portland. 82^{nd} Ave provides a means of north and south connectivity on the east side of the Willamette River. The roadway runs parallel to Interstate-205 and intersects US 26 and I-84. It also provides one of the few entrances into PDX.

Version 2:

From Version 1, the Burnside Bridge and the Sandy Blvd. overpass along I-84 were identified as vulnerable links. The capacity of the Burnside Bridge, Sandy Blvd. overpass and affected I-84 links in both directions were set to zero. The shortest path travels along Davis St, 4^{th} Ave, Flanders St, 6^{th} Ave, Glisan St, Broadway, Weidler St, Wheeler Ave, Williams Ave, Killingsworth St, Martin Luther King Jr. Blvd, Ainsworth St, 27^{th} Ave, Dekum St, Columbia Blvd and 82^{nd} Ave, refer to Figure 12, where the shortest path is highlighted in red. Williams Ave and Vancouver Ave are potential alternative routes. Williams Ave and Vancouver Ave complement each other as they are one way streets traveling north and south, respectively. Once again, Martin Luther King Jr. Blvd, Columbia Blvd. and 82^{nd} Ave appear on the shortest path after several modifications.

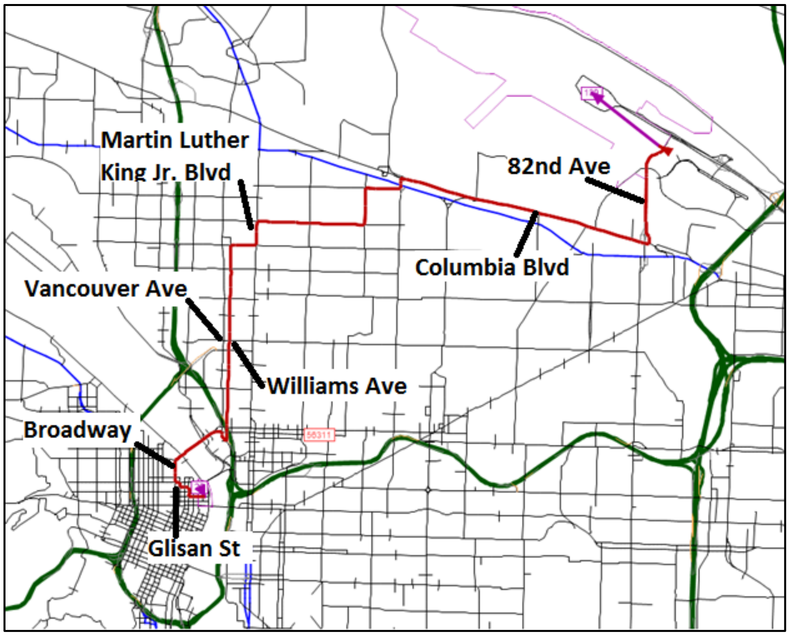

Figure 12: Shortest Path from ODOT to PDX – Version 2

The Broadway Bridge began construction in 1911. It consists of several spans totaling 1,613 feet including two Pennsylvania-Petit Through truss spans, a double-leaf Rall bascule span and a Warrant Through truss span. Given that it is a complicated bridge, it takes up to 4 times longer to open than other bridges crossing the Willamette River such as Morrison or Burnside (Multnomah County, n.d.). Hamilton Construction Company completed a rehabilitation project which included a substructural steel retrofit, replacement of the bridge deck with fiber reinforced polymer deck panels and installation of new streetcar tracks in March 2011 (Hamilton Construction, n.d.). However, it has not be seismically retrofitted (Showman, 2013). The ODOT Portland Office, Portland General Electric (PGE) and Portland Water Bureau are all located near the Broadway Bridge. The Broadway Bridge was deemed a vulnerable link.

Williams Ave and Vancouver Ave travel parallel to both Interstate-5 and Martin Luther King Jr. Blvd, a previously identified alternative route. Williams Ave and Vancouver Ave are both one-way roadways between Winning Way and Killingsworth St traveling north and south, respectively, through residential and commercial areas. There are not bridges or overpasses along either roadway increasing the likelihood of accessibility after a seismic event. It is important to note that the exact destruction to the transportation network after a seismic event is hard to predict. There are power lines and utility poles along these roadways that could influence the usability of the roadway after a seismic event.

<u>Version 3:</u>

From Version 2, Broadway Bridge and the off ramp from 33rd Ave over Columbia Blvd were identified as vulnerable links. Previously Columbia Blvd. was identified as a potential alternative route, however since the shortest path re-routed back to Columbia Blvd, the impact of its inaccessibility was addressed. The capacity of Broadway Bridge, the section of Columbia Blvd under the 33rd Ave overpass, and the 33rd Ave overpass in both directions was set to zero. The shortest path travels along Davis St, 4th Ave, Flanders St, Glisan St, I-405 NB, Fremont Bridge, Cook St, Vancouver Ave, Stanton St, Williams Ave, Killingsworth St, 15th Ave, Dekum St, 27th Ave, Lombard St, Columbia Blvd, Alderwood Rd and 82nd Ave, refer to Figure 13 where the shortest path is highlighted in red. Killingsworth could be a potential alternative route as it travels east and west from the Willamette River to the Interstate-205. Not surprisingly, Vancouver Ave, Williams Ave, Lombard St, Columbia Blvd and 82nd Ave were included in the shortest path.

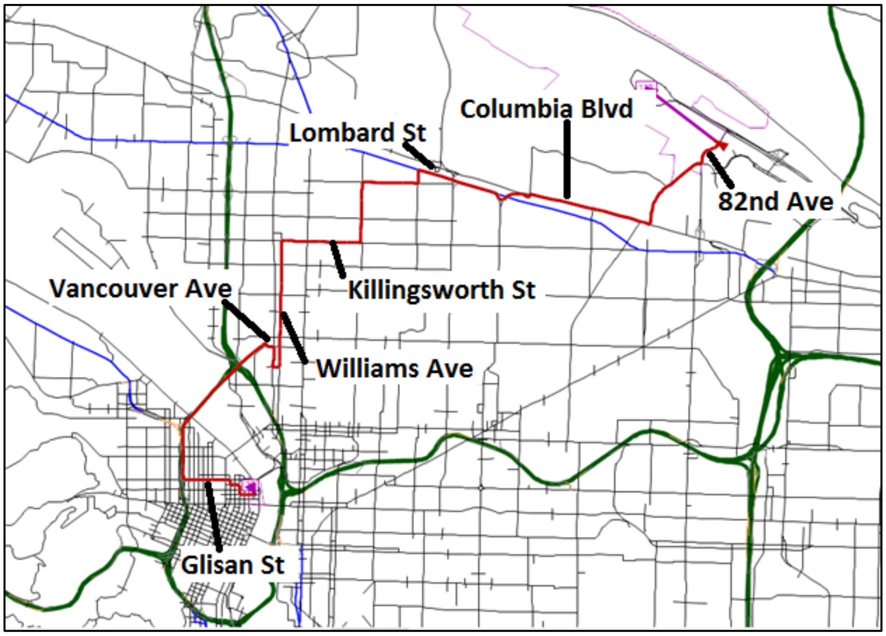

Figure 13: Shortest Path from ODOT to PDX – Version 3

The Fremont Bridge on the I-405 spans the Willamette River connecting the downtown Portland area with North Portland. The Fremont Bridge is a tied-arch bridge and has the longest main span in Oregon totaling 1,255 feet. In 2010, it was estimated that the average traffic was 116,700 vehicles per day with 10% trucks. This bridge was constructed in 1973 and has not had a major repair or reconstruction to meet the new seismic requirements (Wikipedia, n.d.). The Oregon Department of Transportation (ODOT) Portland Office, Portland General Electric (PGE) and Portland Water Bureau are all located in the downtown area. The Fremont Bridge provides one access point to several Port of Portland locations across the river including the Portland International Airport. There are power lines located under the bridge on both ends, as shown in Figure 14. The CH2MHill "Seismic Lifelines Evaluation, Vulnerability Synthesis and Identification" report (CH2MHill, 2012) also identified this section as a tier 1 route based on its connection between I-5 and US 30, access to fuel and Portland circulation. Oregon Department of Geology and Mineral Industries report that the Fremont Bridge is also used for liquid fuel distribution. The Freemont Bridge was deemed a vulnerable link.

Figure 14: Fremont Bridge (I-405) with Nearby Power Lines – South End Source - (Google Maps)

As stated above, Killingsworth St. runs east and west from Swan Island near the Willamette River to Interstate-205. Killingsworth St. intersects Interstate-5, Martin Luther King Jr. Blvd and Portland Highway.

Version 4:

From the third version it is evident, and not surprising, that the shortest path will reroute to the next closest bridge. The last shortest path iteration tries to mimic the worst case scenario if all the bridges except the Marquam Bridge is impassible. In addition to the previous capacity reductions made in Version 1-3 all of the bridges that span the Willamette River were set to zero with the exception of the Marquam Bridge. The Marquam Bridge has been seismically retrofitted. The shortest path travels along Davis St, 3rd Ave, Couch St, Broadway, I-405 SB, I-5 NB, Portland Blvd, Martin Luther King Jr. Blvd, Dekum St, 33rd Ave, Columbia Blvd, Alderwood Rd and 82nd Ave, refer to Figure 15 where the shortest path is highlighted in red. Since there weren't any new alternative routes identified, this was the last iteration.

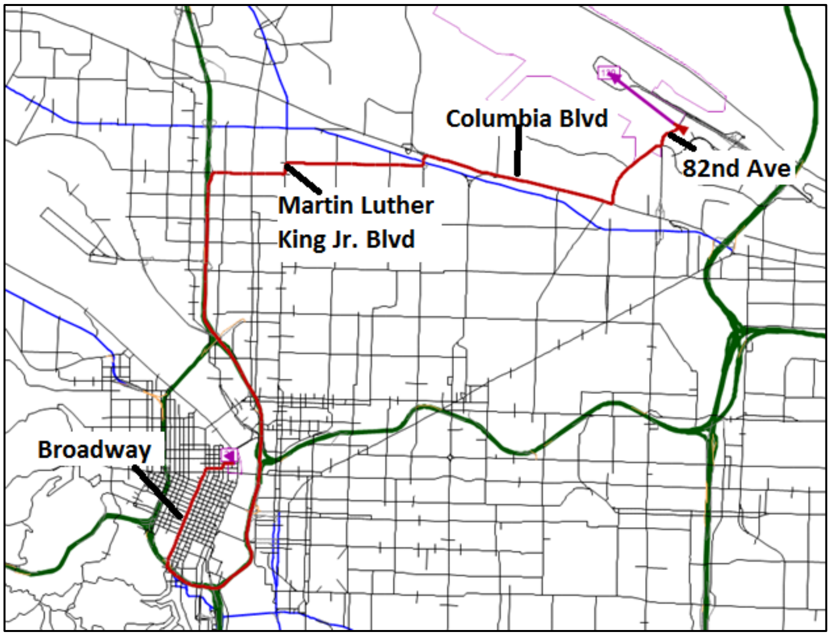

Figure 15: Shortest Path from ODOT to PDX – Version 4

4.1.2 Version Comparison

The version comparison analysis investigated the difference in volume between the scenario and the base version. The pink indicates an increase in volume for that link from the base version. The red indicates a decrease in volume for that link from the base version. For example, Base versus Version 1 we see a clear reduction in volume across the Steel Bridge because it was deemed a vulnerable link and the capacity was reduced to zero, refer to Figure 16. No vehicles were able to travel across the Steel Bridge in the first scenario. There is an increase in volume on nearby bridges such as Burnside, Broadway, Fremont Morrison and Hawthorne. The traffic redistributes itself onto the other bridges that span the Willamette River. Martin Luther King Jr. Blvd. also see an increase in volume.

There is a major volume reduction along Interstate-84 in Version 2 versus the Base version, refer to Figure 17.Version 2 involves a capacity reduction on the Burnside Bridge, Sandy Blvd. overpass at I-84 and all affected I-84 links. Since I-84 is inaccessible after Sandy Blvd, the traffic redistributed itself onto the adjacent streets surrounding the overpass including Burnside St, Glisan St, Broadway, Martin Luther King Jr. Blvd, and sections of Columbia Blvd. and Sandy Blvd. The traffic utilizes the local roadways to avoid the obstacle along Interstate-84 in order to reach 82nd Ave and finally the airport.

The version comparison between the base network and version 3 and 4 are similar to version 2, refer to Figure 18 and Figure 19. The traffic utilizes the same alternative routes (Burnside St, Glisan St, Broadway, Martin Luther King Jr. Blvd, and sections of Columbia Blvd. and Sandy Blvd.) to redistribute as additional links undergo a capacity reduction during the analysis, while the magnitude slightly varies.

<u>Base V.S Version 1:</u>

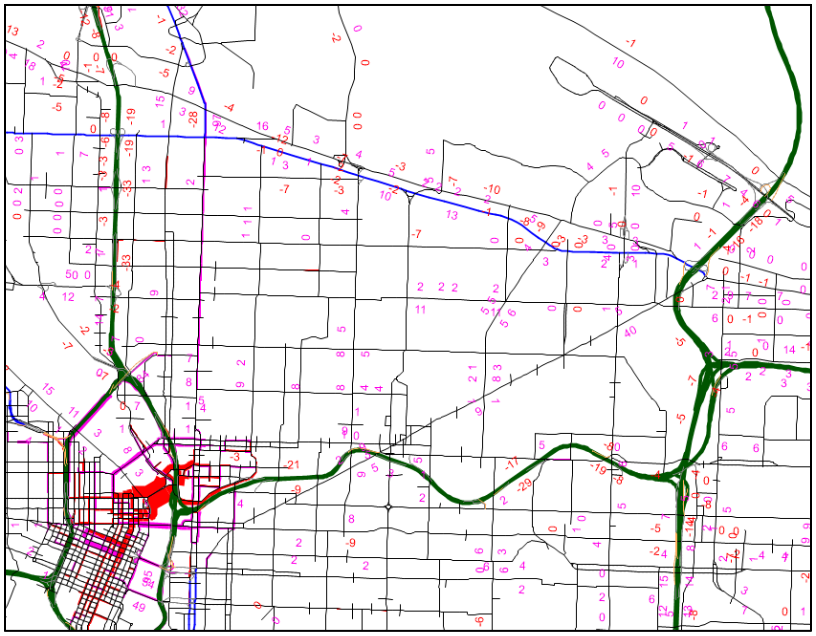

Figure 16: Volume Comparison (Version 1 - Base) for ODOT to PDX Scenario

<u>Base V.S Version 2:</u>

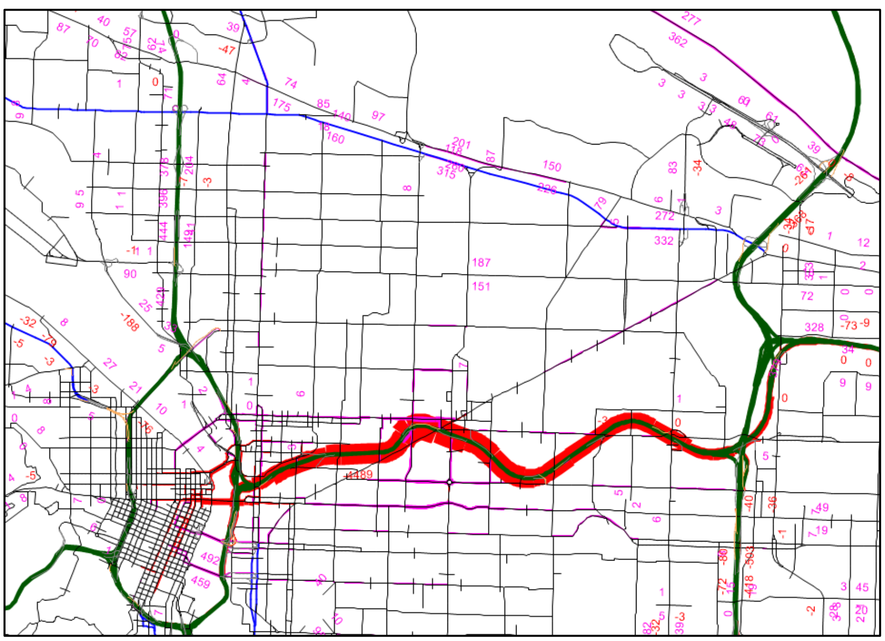

Figure 17: Volume Comparison (Version 2 - Base) for ODOT to PDX Scenario

<u>Base V.S Version 3:</u>

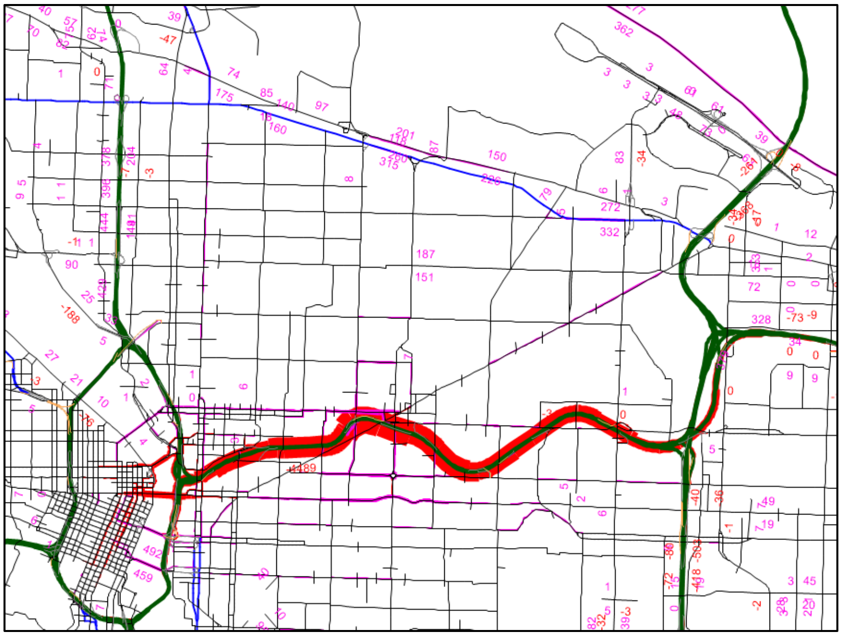

Figure 18: Volume Comparison (Version 3 - Base) for ODOT to PDX Scenario

Base V.S Version 4:

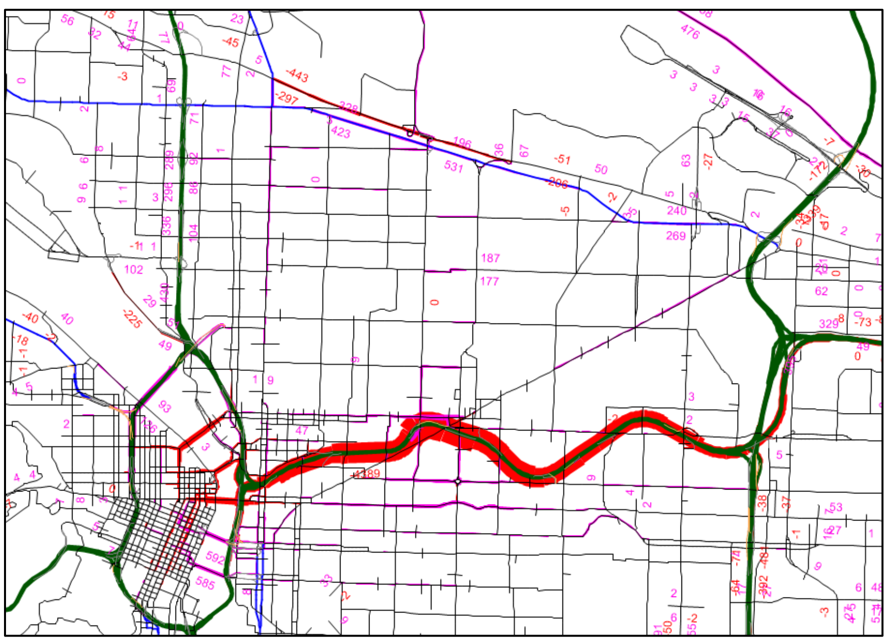

Figure 19: Volume Comparison (Version 4 - Base) for ODOT to PDX Scenario

4.1.3 Accessibility Analysis

The accessibility analysis tool in VISUM demonstrates the travel time needed to reach a particular link from a starting zone. ODOT was selected as the starting zone and the darker colors represent longer travel times. It is evident that as more a more links see a decrease in capacity the travel times continue to increase, as shown in Figure 20. Version 4 emulates the worst case scenario, if only the Marquam Bridge is usable after an event. The accessibility analysis reveals that any destination to the east of the Willamette river will require more than 50 minutes to reach.

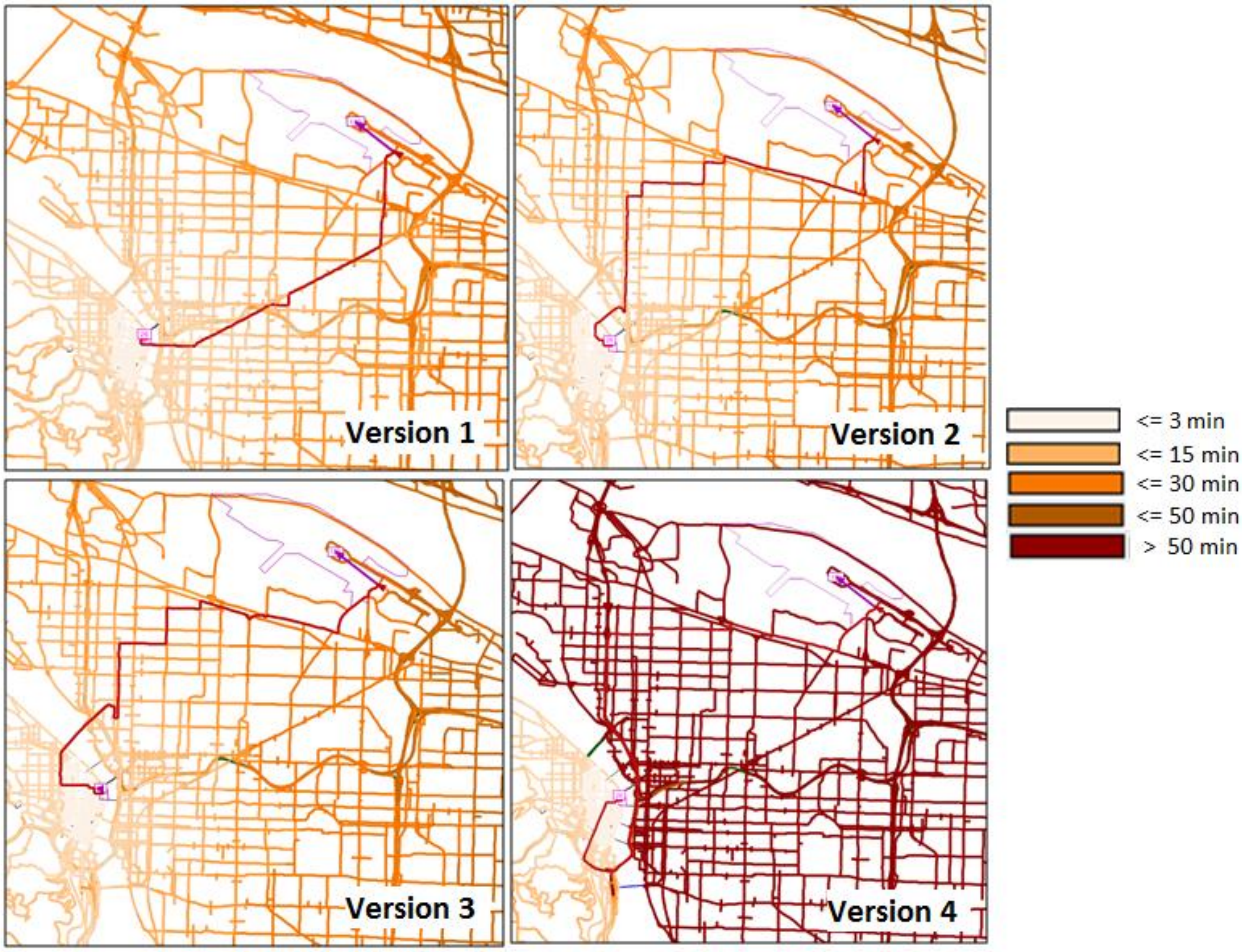

Figure 20: Results from the Accessibility Analysis Traveling from ODOT

4.2 BONNEVILLE POWER ADMINISTRATION TO PORTLAND INTERNATIONAL AIRPORT

4.2.1 Shortest Path (travel time)

Base Version:

The shortest path travels along 13th Ave, Multnomah St, 21st Ave, Fremont St, 24th Ave, 29th Ave, Prescott St, Cully Blvd, Killingsworth St, Portland Hwy and 82nd Ave, refer to Figure 21 where the shortest path is highlighted in red. Potential alternative routes include Prescott St, Cully Blvd, Killingsworth and 82nd Ave. Killingsworth and 82nd Ave were previously identify as alternative routes in the ODOT to PDX scenario. Prescott St is a main arterial from east to west, connect 99E and I 205, serves as an importation link between two main routes. No overpass or bridges on this road also make it a safer alternative route. NE Cully Blvd connects Prescott St and Killingworth St, as an arterial, it directs traffic to the NE Portland Hwy and saves much travel time.

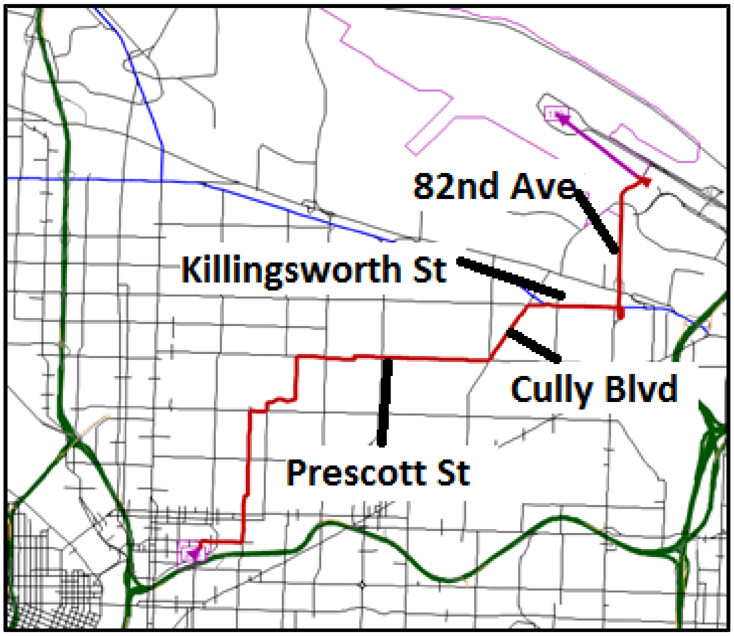

Figure 21: Shortest Path from BPA to PDX - Base Version

Version 1:

Since both Killingsworth St. and 82nd Ave. were identified as alternative routes in the previous scenario sections of those roadways were simulated to fail. In order to identify all possible local roadways that can be utilized in evacuation and recovery efforts the capacity of Killingsworth St. and 82nd Ave. where they cross over one another were set to zero. This will help to highlight other nearby local roads. The shortest path travels along 13th Ave, Multnomah St, 21st Ave, Fremont St, 24th Ave, 29th Ave, Prescott St, 33rd Ave, Killingsworth St, 42nd Ave, 47th Ave, Cornfoot Dr, Alderwood Rd and 82nd Ave, refer to Figure 22 where the shortest path is highlighted in red. Potential alternative routes include Cornfoot Dr. and Alderwood Rd. One vulnerable area along the route is the 42nd Ave. overpass above the Portland Hwy.

Cornfoot Dr. run parallel to a portion of Lombard St. and Portland Hwy. If both of those previously identified alternative routes are impassible, Cornfoot Dr. could be used as an alternative route. When the disaster happens, bridges and overpasses are most vulnerable parts of a network. No overpass or bridge ensure Cornfoot Dr. a safe alternative route to evacuate.

Alderwood Rd. can sever as another connector road to PDX. It intersects Lombard St. and can be used as another passage way to the airport if portions of 82nd Ave. are damaged. The junction connected NE 82nd Ave, NE Killingsworth St and NE Columbia Blvd are risky to travel due the overpass, NE Alderwood Rd pass the vulnerable section and connect the Ne Airport way directly, it would serve as a reliable alternative route.

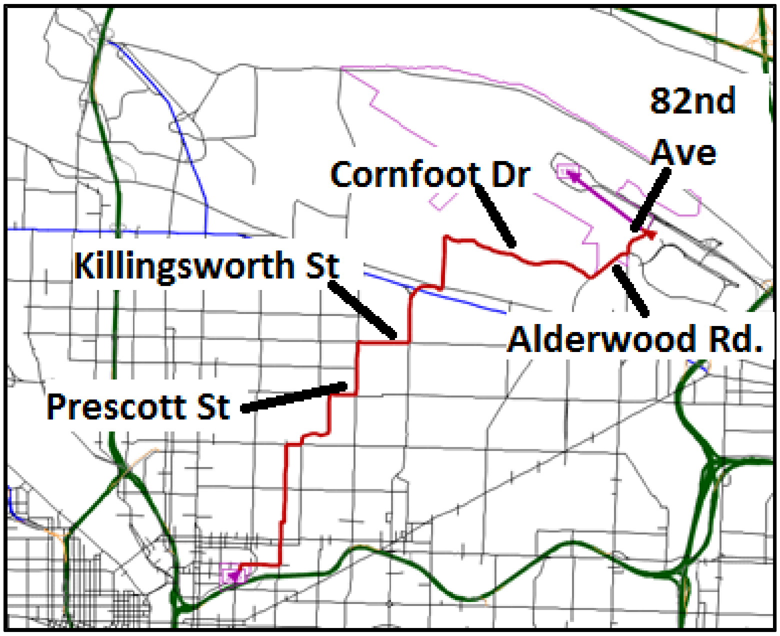

Figure 22: Shortest Path from BPA to PDX - Version 1

Version 2:

The vulnerable overpass on 42nd Ave. and the affected portions of Portland Hwy experienced a reduction in capacity. As mentioned many time before, overpasses and bridges are the most susceptible parts of the network to damage due to an earthquake. The shortest path after the capacity reductions rerouted to travel along 13th Ave, Multnomah St, 21st Ave, Knott St, 24th Ave, 29th Ave, Prescott St, Cully Blvd, Columbia Blvd and 82nd Ave, refer to Figure 23 where the shortest path is highlighted in red. There are no new alternative routes.

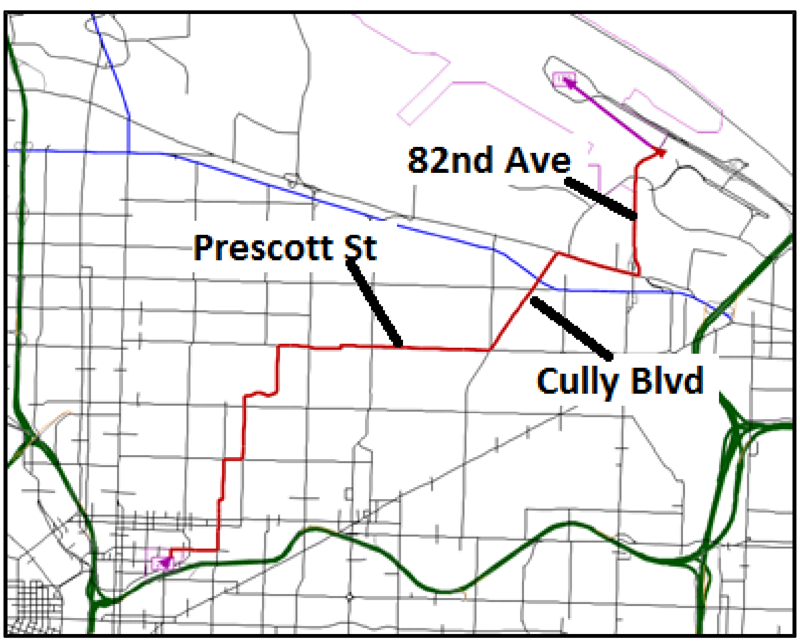

Figure 23: Shortest Path from BPA to PDX - Version 2

4.2.2 Version Comparison

Again, the version comparison analysis investigated the difference in volume between the scenario and the base version. The pink indicates an increase in volume for that link from the base version. The red indicates a decrease in volume for that link from the base version. For example in Figure 24, the capacity on the roadways that could be affected by the collapse of the Killingsworth St. overpass above 82nd Ave were set to zero which explains the heavy red color in the area. Since the traffic is unable to travel though either Killingsworth St. or 82nd Ave at the intersection the volume of the roads nearby increase which is represented by the green bars. Specifically, Cornfoot Dr. and Alderwood Rd. experience an increase in traffic which is one reason they are both deemed a potential route.

The second iteration or version incorporates another capacity modification at the crossing of 42nd Ave. and Portland Hwy. This modification results in a major volume reduction along Columbia Blvd and Portland Hwy, refer to Figure 25. This analysis further highlights the importance of both Columbia Blvd and Portland Hwy for airport accessibility.

<u>Version 1:</u>

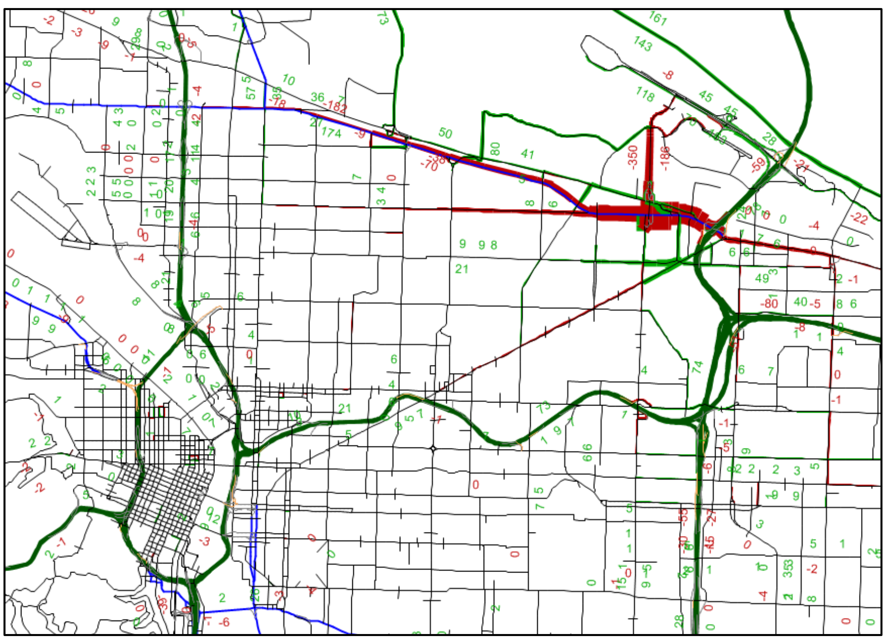

Figure 24: Volume Comparison (Version 1 - Base) for BPA to PDX Scenario

<u>Version 2:</u>

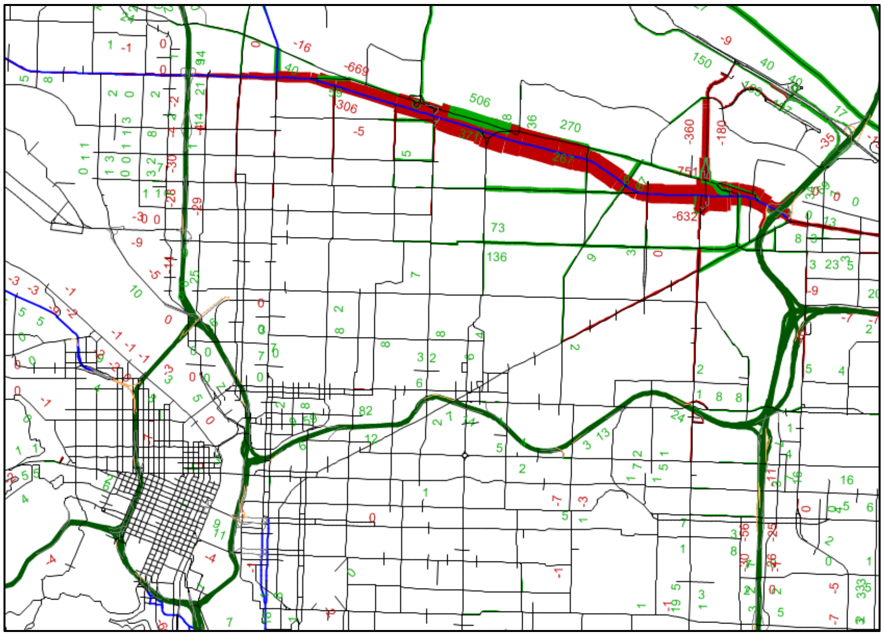

Figure 25: Volume Comparison (Version 2 - Base) for BPA to PDX Scenario

4.2.3 Accessibility Analysis

Again, he accessibility analysis tool in VISUM demonstrates the travel time needed to reach a particular link from a starting zone. BPA was selected as the starting point. Figure 26 shows the amount of time it will take a vehicle to travel to each point in the network. As more roadways are simulated as damaged the accessibility difference is subtle. This scenario and each version of the network show that the max travel time is about 30 minutes to any point in the network.

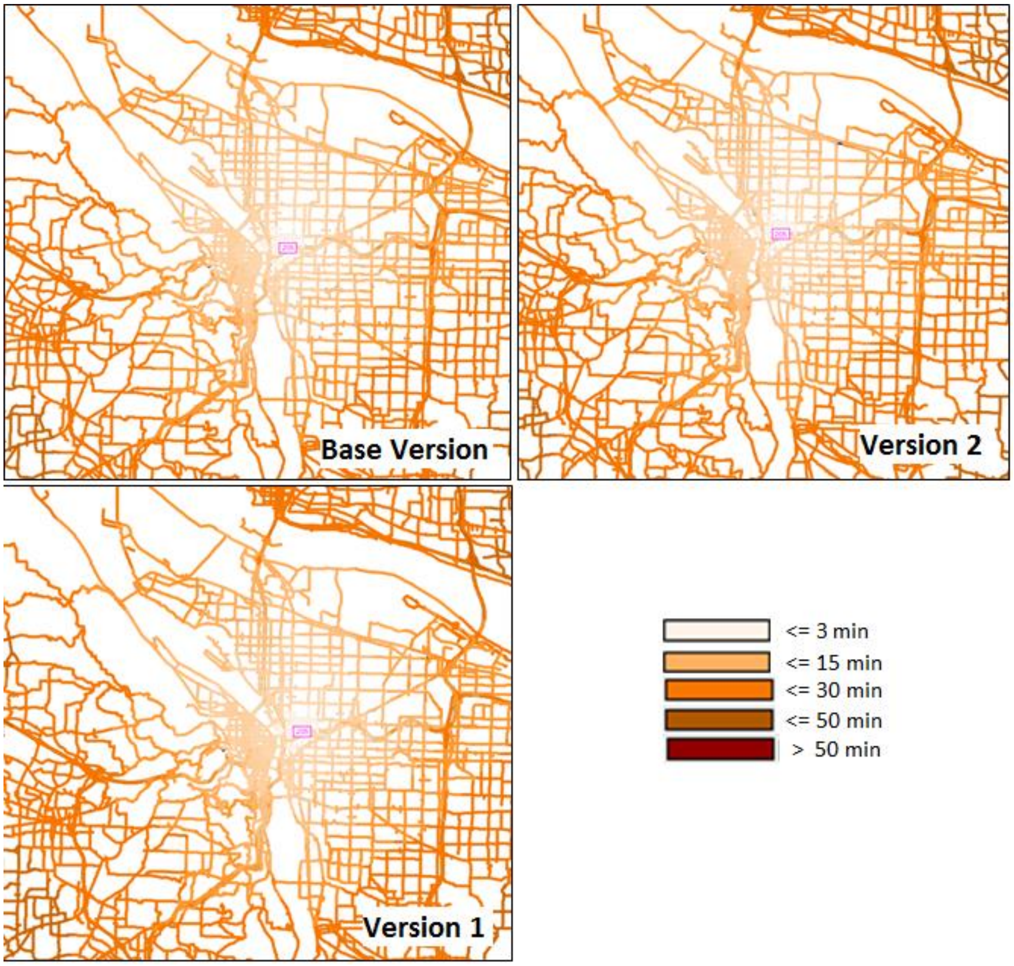

Figure 26: Results from the Accessibility Analysis Traveling from BPA

4.3 PORT OF PORTLAND TO BEND

4.3.1 Shortest Path (travel time)

Base Version:

The shortest path travels along Burgard Rd, Columbia Blvd, Portland Rd, Marine Dr, 185^{th} Ave, Sandy Blvd, 207^{th}, Hasley St, 223^{rd} Ave, Burnside Rd and US 26 refer to Figure 27 where the shortest path is highlighted in red. Marine Dr. is a potential alternative route. Columbia Blvd and Sandy Blvd have already been identified as a potential alternative route in pervious scenarios. Along the Columbia River, Marine Dr. has fewer intersections, traffic lights, bridges and overpass; it is safer and save the travel time to evacuate from Portland to Bend. Connecting to I205 and I84 makes it more accessible when a reroute is needed.

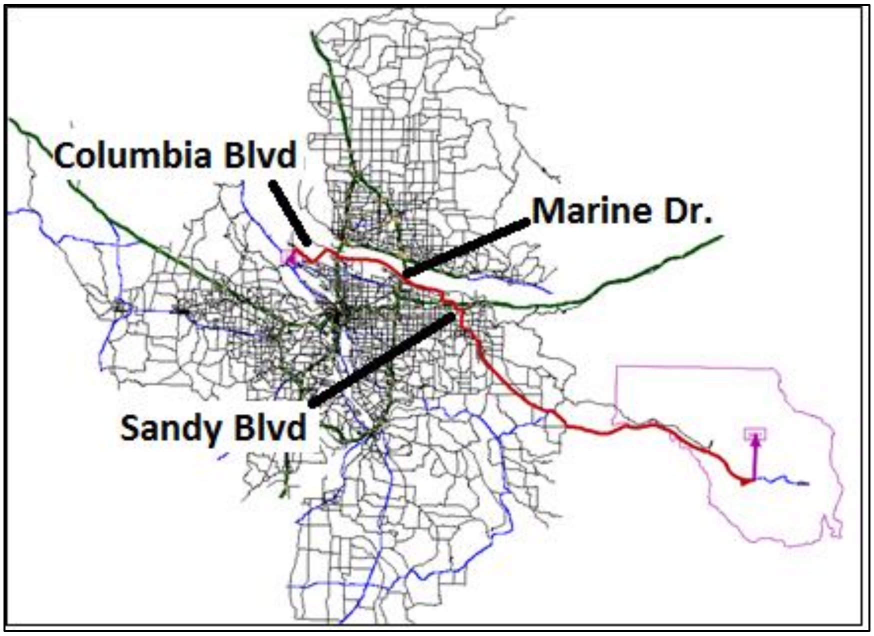

Figure 27: Shortest Path from Port of Portland to Bend - Base Version

Version 1:

All of the bridges and overpasses along the shortest path from the base version were eliminated. The capacity of Columbia Blvd overpass above Portland Rd/Columbia Way, Martin Luther King Jr. Blvd overpass above Marine Way, Glenn Jackson Memorial Bridge above Marine Dr. and Compton Rd. overpass above US 26 were set to zero. The shortest path now travels along Burgard Rd, Columbia Blvd, Lombard Pl, Lombard St, Portland Hwy, Killingsworth St, I-205 SB, I-84 EB, 207th Ave, Glisan St, 223rd Ave, Burnside Rd, Hogan Ave, Powell Blvd, US 26, off ramp towards Boring, Oregon in order to avoid the Compton Rd. overpass and back on to US 26 refer to Figure 28 where the shortest path is highlighted in red. Potential alternative routes include 223rd Ave/ Fairview Ave, Burnside Rd and Powell Blvd. Columbia Blvd, Lombard St, Killingsworth and Glisan St have already been identified as potential alternative routes. With less overpass and bridges, this is main advantage that 223rd Ave/ Fairview Ave, Burnside Rd and Powell Blvd would serve as the alternative route. In addition, not like the other local route, these three routes have larger capability to serve as a route to evacuate. Roads with small capacity hardly being utilized as a lifeline, congestion on that road would make them more vulnerable. Less traffic control device and easy access to other arterials make it a reliable alternative route.

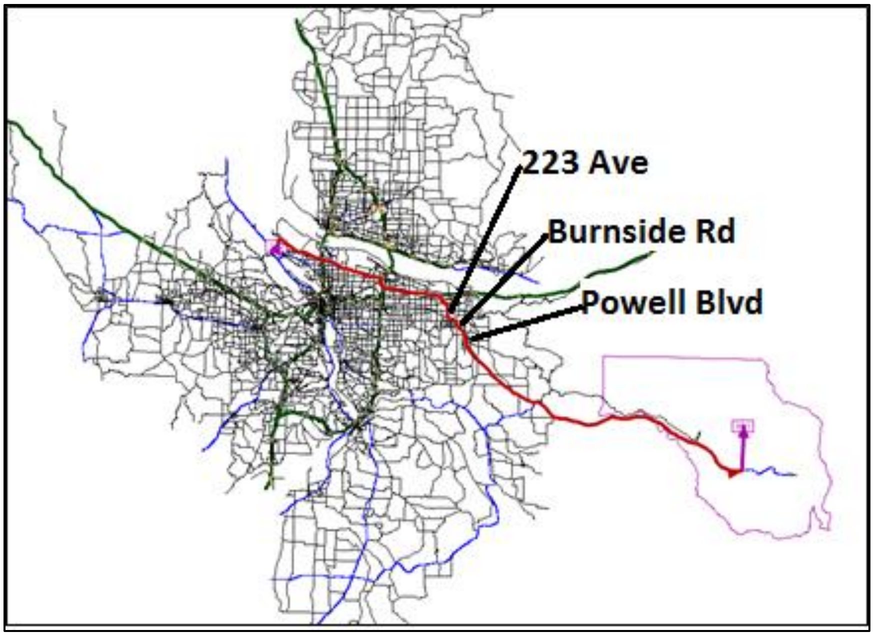

Figure 28: Shortest Path from Port of Portland to Bend - Version 1

Version 2:

The capacity of the following overpasses were reduced to zero Columbia Blvd & I-5, Sandy Blvd & I-205, Prescott St & I-205, 148th Ave & I-84, 162nd Ave & I-84, 181St Ave & I-84, 201St Ave & I-84, Fairview Pkwy & I-84 and 282nd Ave & Mt Hood Hwy. The new shortest path travels along Lombard St, Chautauqua Blvd, Portland Blvd, I-5 SB, Belmont St, 7th Ave, Division St, 21st Ave, Powell Blvd, 72nd Ave, Foster Rd, Woodstock Blvd, Foster Rd, Clackamas Hwy and US 26, refer to Figure 29 where the shortest path is highlighted in red. Potential alterative routes are Division St. and Foster Rd. Again, Lombard St. and Powell Blvd have already been identifies as potential alternative routes. As another main route link many main routes between 99E and I205, Division St. has a good capability to distribute the traffic. No vulnerable overpass or bridges make it superior to other routes. SE Foster Rd connects SE Powell Rd, SE 82nd Ave and I205, all the way down to the Mt Hood Hwy. With enough capacity but avoid the busy local districts, Foster Rd saves the evacuation time and safer to travel on.

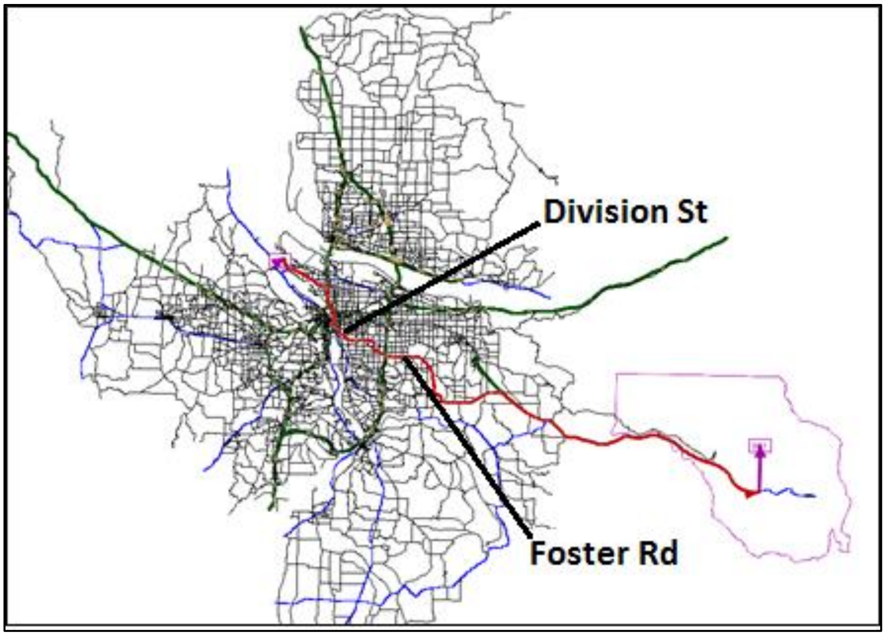

Figure 29: Shortest Path from Port of Portland to Bend - Version 2

4.3.2 Version Comparison

The version comparison tool in VISUM allows a deeper investigate into the network by calculating the difference in volume after modifications to the network. Although version 1 had many modifications the change in volume, either an increase or decrease in volume along each link in the network, was relatively small, refer to Figure 30. On the other hand, there were significant changes in volume after the version 2 modifications were added, refer to Figure 31. There is a major volume reduction along I-84 and I-205 where they intersect. There is also a notable decrease in volume along I-5 near the Columbia River.

<u>Version 1:</u>

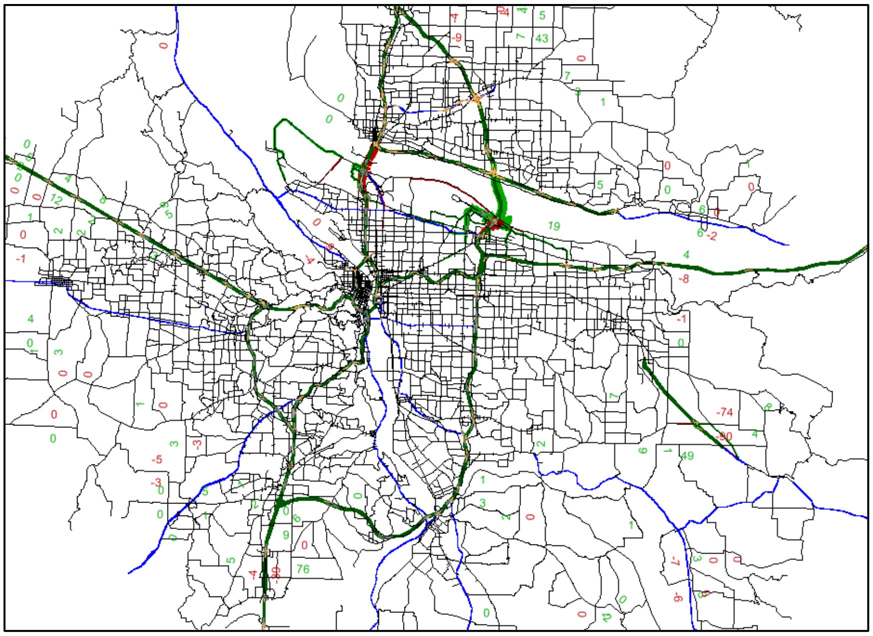

Figure 30: Volume Comparison (Version 1 - Base) for Port of Portland to Bend Scenario

Version 2:

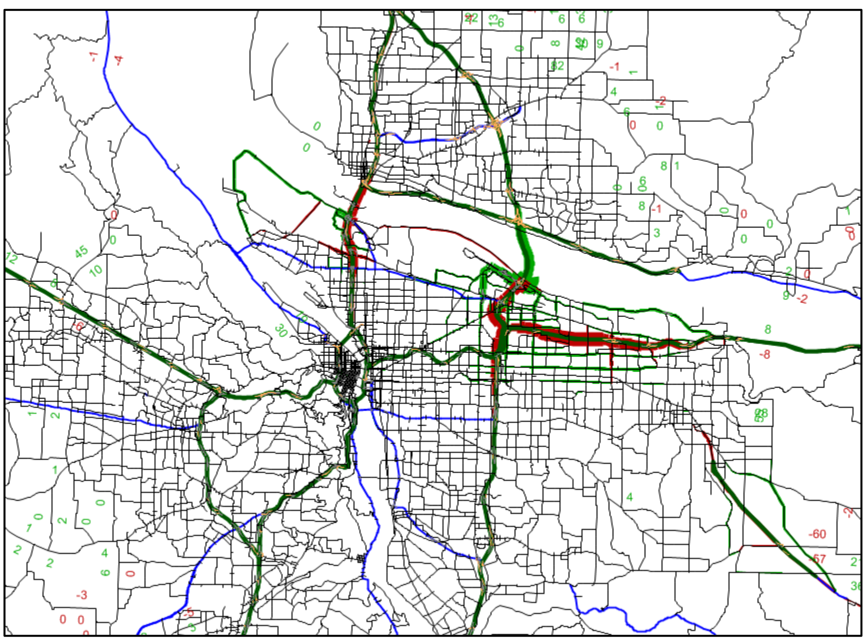

Figure 31: Volume Comparison (Version 2 - Base) for Port of Portland to Bend Scenario

4.3.3 Accessibility Analysis

The accessibility analysis revealed the travel time from one selected point in the network to the rest of the network. The Port of Portland was selected as the starting point. The Port of Portland's remote location yields high travel times in the base version with no modifications. As more links are simulated as damaged or impassible the travel times increase. After the first round of modifications (i.e. Version 1) it will take greater than 50 minutes to travel across the Columbia River into Washington and the southeastern section of Portland, refer to Figure 32. The travel time only increases as the second round of modifications are implemented.

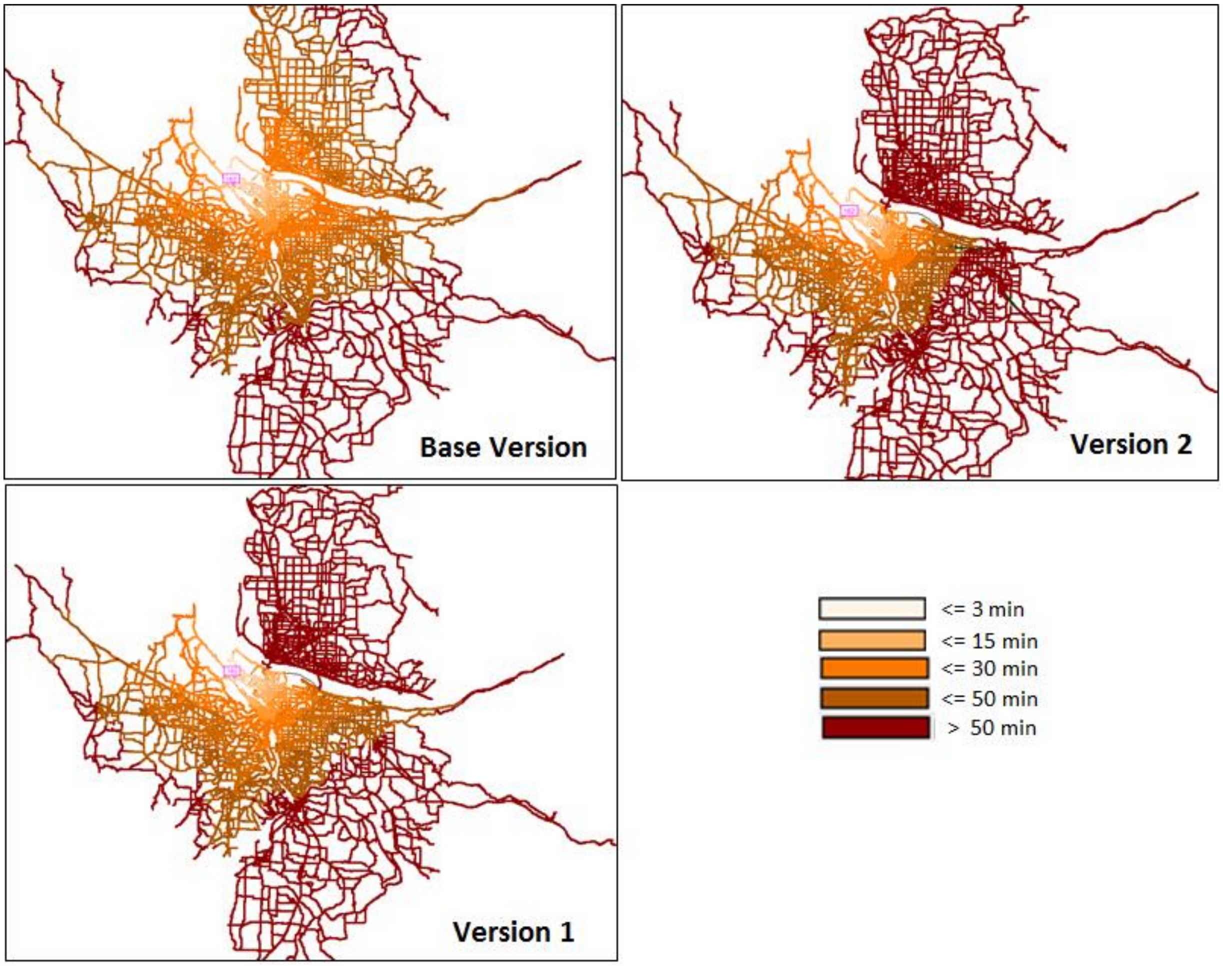

Figure 32: Results from the Accessibility Analysis Traveling from the Port of Portland

5.0 OTHER MODES OF TRANSPORTATION

Like the other cities in U.S, the primary local transportation mode in Portland, Oregon is automobile. In this report, the lifeline is based on the vehicle evacuation. However, Portland also gains the reputation for the well-planned public transit system. In 2008, the rate of public transit use in Portland reached 12.6% (Wikipedia, n.d.). Relying on the advanced public transportation tool, not all the people have a vehicle to get out from Portland. Thus, when conduct an evacuation research for Portland, neglecting public transit system would obviously lead to an incomprehensive evacuation plan since some of the people has no car to evacuate. Therefore, in the next phase of this project, transit system would be incorporated in lifeline selection. Other than the light rail, streetcar and buses, rail system also plays a significant role in Portland's transportation. When the selected lifeline has trouble in transporting people out of the Portland, railway is a good way for the evacuation. In the future work, rail system could also be considered as an alternative way to investigate.

Considering the worst case that all the bridges clasped, the east side of the river would be isolated. As the Willamette River flows through the city, water transportation may also be considered as a potential way to transport goods and people.

Another interesting transportation is bicycle, which also consist a really large part of transportation in Portland. Approximately 8% of commuters bike to work in Portland, which is highest in major U.S city (Wikipedia, n.d.). This type of transportation is hard to measure and incorporate into our research due to the lack of the data, but this unique feature of transportation in Portland worth investigating in other researches.

6.0 CONCLUSION AND FUTURE WORK

7.0 REFERENCES

Adams, T., Bekkem, K., Bier, V., 2010. Operational Resiliency of Beloit-Hudson Interstate Highway Corridor.

Ag, P.T. V, n.d. PTV Visum13 – User Manual.

CH2MHill, 2012. Seismic Lifelines Evaluation , Vulnerability Synthesis , and Identification.

Chiu, Y.-C., Zheng, H., Villalobos, J. a, Peacock, W., Henk, R., 2008. Evaluating Regional Contra-Flow and Phased Evacuation Strategies for Texas Using a Large-Scale Dynamic Traffic Simulation and Assignment Approach. J. Homel. Secur. Emerg. Manag. 5. doi:10.2202/1547-7355.1409

CityData, n.d. Bridge Statistics for Portland, Oregon - Condition Traffic, Stress, Structural Evaluation, Project Costs [WWW Document]. URL citydata.com (accessed 5.28.14).

Dow, K., Cutter, S.L., 2002. Emerging Hurricane Evacuation Issues : Hurricane Floyd and South Carolina 12–18.

Frangopol, D., Bocchini, P., 2011. Resilience as Optimization Criterion for the Rehabilitation of Bridges Belonging to a Transportation Network Subject to Earthquake 2044–2055.

Frazier, T.G., Thompson, C.M., Dezzani, R.J., Butsick, D., 2013. Spatial and temporal quantification of resilience at the community scale. Appl. Geogr. 42, 95–107. doi:10.1016/j.apgeog.2013.05.004

Freckleton, D., Heaslip, K., Louisell, W., Collura, J., 2012. Evaluation of Resiliency of Transportation Networks After Disasters. Transp. Res. Rec. J. Transp. Res. Board 2284, 109–116. doi:10.3141/2284-13

Friedrich, M., 2008. Modelling Through Traffic Prohibition.

Hamilton Construction, n.d. Project: Broadway Bridge / Portland Streetcar [WWW Document]. URL http://www.hamil.com/projects_broadway.php (accessed 8.13.14).

Henrichsen, J., 2002. Seismic Walking Tour Guide.

Horner, M.W., Widener, M.J., 2011. The effects of transportation network failure on people's accessibility to hurricane disaster relief goods: a modeling approach and application to a Florida case study. Nat. Hazards 59, 1619–1634. doi:10.1007/s11069-011-9855-z

Kiremidjian, A., Moore, J., Fan, Y.Y., Yazlali, O., Basoz, N., Williams, M., 2007. Seismic Risk Assessment of Transportation Network Systems. J. Earthq. Eng. 11, 371–382. doi:10.1080/13632460701285277

Leu, G., 2010. Resilience of ground transportation networks : a case study on Melbourne Resilience of ground transportation networks : a case study on Melbourne.

Miller-Hooks, E., Krauthammer, T., 2006. An Intelligent Evacuation, Rescue and Recovery Concept. Fire Technol. 43, 107–122. doi:10.1007/s10694-006-8433-5

Montz, T., Asce, A.M., Dixit, V., Ph, D., Wilmot, C., Asce, M., Wolshon, B., 2013. Assessing the Effectiveness of Flexible Response in Evacuations 200–210. doi:10.1061/(ASCE)NH.1527-6996.0000101.

Multnomah County, n.d. Broadway Bridge | Multnomah County [WWW Document]. URL https://multco.us/bridges/broadway-bridge (accessed 8.13.14).

Neves, R., 2011. Experts: After quake, Marquam Bridge Holds Up. KGW News.

Orabi, W., 2011. A Web-Based Resource Management System for Damaged Transportation Networks 810–817.

Orabi, W., Asce, S.M., El-rayes, K., Asce, M., Senouci, A.B., Al-derham, H., 2009. for Damaged Transportation Networks 1039–1048.

Oregon Department of Transportation, 2009. Seismic Vulnerability of Oregon State Highway Bridges.

Ozbay, K., Yazici, M.A., Iyer, S., Li, J., Ozguven, E.E., Carnegie, J. a., 2012. Use of Regional Transportation Planning Tool for Modeling Emergency Evacuation. Transp. Res. Rec. J. Transp. Res. Board 2312, 89–97. doi:10.3141/2312-09

Pant, S.B., 2012. Transportation Network Resiliency : A Study of.

Sánchez-Silva, M., Daniels, M., Lleras, G., Patiño, D., 2005. A transport network reliability model for the efficient assignment of resources. Transp. Res. Part B Methodol. 39, 47–63. doi:10.1016/j.trb.2004.03.002

Showman, S., 2013. How safe are the bridges of Portland? KOIN6 News.

Talbot, J., 2012. Portland ' s 1912 Steel Bridge : Setting the Standard for Multi-modal Transport. Mod. Steel Constr. 1912–1915.

Tamvakis, P., Xenidis, Y., 2013. Comparative Evaluation of Resilience Quantification Methods for Infrastructure Systems. Procedia - Soc. Behav. Sci. 74, 339–348. doi:10.1016/j.sbspro.2013.03.030

Tzeng, G.-H., Cheng, H.-J., Huang, T.D., 2007. Multi-objective optimal planning for designing relief delivery systems. Transp. Res. Part E Logist. Transp. Rev. 43, 673–686. doi:10.1016/j.tre.2006.10.012

Univeristy of California Los Angelos, n.d. EERI Student Chapter Home Page [WWW Document]. URL http://www.studentgroups.ucla.edu/eeri/ (accessed 8.13.14).

USGS, 2014. Recent Earthquake Near Oregon, United States [WWW Document]. URL http://earthquaketrack.com/p/united-states/oregon/recent (accessed 5.28.14).

Wang, Y., Bartlett, S.F., Miles, S.B., 2012. Earthquake Risk Study for Oregon ' s Critical Energy Infrastructure Hub.

Wikipedia, n.d. Burnside Bridge [WWW Document]. URL http://en.wikipedia.org/wiki/Burnside_Bridge (accessed 5.28.14a).

Wikipedia, n.d. Fremont Bridge (Portland) [WWW Document]. URL http://en.wikipedia.org/wiki/Fremont_Bridge_(Portland) (accessed 5.28.14b).

Wikipedia, n.d. Transportation in Portland, Oregon [WWW Document]. URL http://en.wikipedia.org/wiki/Transportation_in_Portland,_Oregon#cite_note-35 (accessed 8.28.14c).