# Post-Disaster Mobility in Disrupted Transportation Network: Case Study of Portland, Oregon

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## ABSTRACT

This paper presents a post-disaster transportation network capacity and mobility analysis through different bridge failure scenarios. The goal of this paper is to investigate the transportation performance under the loss of capacity, and specifically, the bridge failure caused by natural disasters. A specific scenario from ODOT to PDX in City of Portland is developed to examine the travel time variation, and further, the results are validated through a Monte Carlo simulation. In addition, travel time sensitivity and zone to zone travel times are investigated for different failure scenarios to rank the bridges of the network based on their importance. The results show that Portland transportation network is resilient to minor damage until the number of damaged bridges reaches a critical threshold. The results are expected to be used to devise an optimal retrofitting and resource allocation plan to facilitate recovery and business continuity.

## INTRODUCTION

In the Pacific Northwest, a magnitude 9.0 earthquake and resultant tsunami from the Cascadia Subduction Zone (CSZ) represents one of the most pressing natural disasters with 7-12% chance of occurrence by 2060 (Goldfinger et al., 2012). The transportation network is one of the most critical infrastructure networks susceptible to the earthquake. A magnitude 9.0 earthquake is likely to trigger widespread disruptions of the transportation network. The Bridge and Engineering Section of Oregon Department of Transportation (ODOT) developed a Seismic Vulnerability of Oregon State Highway Bridges in November 2009 (ODOT, 2009). ODOT reports that seismic loading was not typically considered prior to 1958. Afterwards, between 1958 and 1974 a seismic load of 2% to 6% of the structural weight was used, and later on, between 1975 and 1990 the seismic load was increased to 8% to 12% of the structural weight. In 1990, the AASHTO Seismic Design Guide was adopted. In addition, earthquakes along the Pacific border, as well as the discovery of previously large subduction zone earthquakes, prompted ODOT to raise their seismic standard. However, infrastructures built before 1975 without retrofitting have significant structural collapse potential. Infrastructure built between 1975 and 1994 should also be considered as moderately critical in terms of structural failure (ODOT, 2009).

To facilitate the implementation of policy that “provides a secure lifeline network of streets, highways, and bridges to facilitate emergency services response and to support rapid economic recovery after a disaster” (ODOT, 2006), Oregon Seismic Lifelines Route Identification (OSLR) project was conducted by the ODOT Transportation Development Division (TDD) from

September 2011 through April 2012 (CH2MHILL, 2012). The project established a three-tiered system of lifeline corridors to prioritize seismic retrofits on state-owned highways and bridges. Although major arterials play a crucial role in connecting different regions supporting emergency response and recovery efforts, OSLR has only focused on the network of highways. Therefore, thorough investigation of comprehensive transportation network is strongly needed. In addition, after the conclusion of seismic events, bridges are the most vulnerable components of the network to be closed or destroyed. Among the 1232 lifeline structures in Oregon, ODOT has identified 713 bridges to be considered seismically vulnerable or potentially seismically vulnerable. Nearly 60 percent of state-identified lifeline bridges in Oregon are expected to be collapsed or be potentially closed after an earthquake (OPB, 2016). The great risk posed by bridge failures on transportation network is hence not negligible. Bridges tend to be the critical component to connect different sections of the transportation network. The capacity loss resulted from bridge failures normally generates more catastrophic influence than a regular roadway link. Therefore, an investigation on the relationship between bridge failure and transportation network mobility, with accounting for comprehensive transportation network, needs to be conducted. In this paper, eight bridges over Willamette River in Portland Metro area are studied and different scenarios are developed to measure the impact of bridges' failure on network's performance. This paper begins by presenting a comprehensive literature review on related topics in Section 2. Section 3 describes the study site and simulation network in this experiment. Section 4 provides the analysis results generated from the proposed framework. Finally, section 5 summarizes the research and discusses important findings.

## LITERATURE REVIEW

Unplanned network disruptions caused by infrastructure failure can be observed from past events. For example, the collapse of the I-80 San Francisco-Oakland Bay Bridge, the I-880 Cypress Street Viaduct, the Hatchie River Bridge in Tennessee, and the I-40 bridge at Webber Falls, Oklahoma etc. (Zhu et al., 2010). While a link damage will affect the network connectivity, a bridge collapse could bring more significant impact on the network mobility. Due to these type of incidents, travelers have to search the network and adjust their travel behavior accordingly.

Existing research efforts have primarily focused on reconstruction strategies, efficient resource distribution systems, and accessibility in a damaged network. Sanchez-Silva et al. (2005) and Horner and Widener (2011) focused on accessibility on a disrupted network. Sanchez-Silva et al. (2005) presented a model for optimizing assignment of resources based on the probabilistic reliability of the transportation network. The proposed methodology utilizes Markov chain modeling of failure states and estimates of expected cost and accessibility to optimize resource allocation. A case study in Columbia is used to illustrate the applicability and the benefits of the model. The results have shown that improvements to the failure rates and focusing on improvements to individual routes yields to higher accessibility. Horner and Widener (2011) investigated the effect of hurricane disaster on the transportation network related to relief distribution center location. Each scenario considered a percentage of randomly selected links of the network to be inaccessible. However, bridges tend to be more vulnerable in a natural disaster. Thus, special consideration for bridges should be included. Kiremidjian et al. (2007) conducted a study to evaluate the total cost associated with damage to bridges and travel time delays of a transportation network due to a seismic event. Chang and Nojima (2001) use total length of network open, total distance-based accessibility, and areal distance-based accessibility as the post-disaster system performance measure to investigated the transportation network in Kobe, Japan, after 1995 Hyogoken-Nanbu earthquake.

It makes sense that earthquake's damage to certain components, i.e., the crucial and non-redundant links within the system, will have a greater impact on the system performance, rather than other components (Werner et al., 1997). Unfortunately, each component is usually treated as an individual entity only, without considering how its damage may affect the system performance. In addition, current criteria for prioritizing bridges for seismic retrofit is bound to average daily traffic count, detour length, and route type as parameters in the prioritization process. Further, current practice does not account for the systemic effects regarding the loss of a given bridge, or for the combinatorial effects associated with the loss of other bridges in the system. These systemic and combinatorial effects can provide a much more rational basis to prioritize the seismic retrofit plan and seismic design for highway components (Buckle, 1992; Moore II, 1997; Werner et al. 1997). This paper specifically investigated the bridge failures' impact on network travel time. Through the sensitivity analysis on each bridge's contribution to the increase of travel time, the importance of different bridges can be rated.

## METHODOLOGY AND STUDY SITE

The simulation network is developed in VISUM. Empirical traffic data with different modes are considered: high occupancy vehicle, single occupancy vehicle, medium truck, and heavy truck. In order to approximate the post-disaster scenario, evening peak hour (5:00pm - 6:00pm) travel demand is considered. Each scenario is developed by reducing the link capacity on the base network and travel time is used as performance measurement. The equilibrium Lohse iterates 40 times for each simulation. Each scenario takes roughly 30 minutes on a desktop computer to simulate and the runtime increases as the number of failed bridges grow.

Portland is the most populated area in Oregon and is home to thousands of businesses, its quick recovery is crucial to business continuity. In addition, the Willamette River creates a unique landscape in Portland, Oregon. The river divides the city into two parts, and bridges over the river become the vital component in the transportation network. Bridge failure is expected to tremendously deteriorate system performance. In this paper, eight bridges over Willamette River in Portland Metropolitan area, as shown in Figure 1(a), including Fremont, Broadway, Steel, Burnside, Morrison, Hawthorne, Marquam, and Ross bridge, are investigated. To extend the scope of the study, surrounding areas such as Vancouver, WA, is also included. There are 2,162 traffic analysis zones (TAZ) in total as in Figure 1(b).

## EXPERIMENT DESIGN AND RESULTS

**Network Accessibility under Bridge Failures:** The Willamette River creates a natural barrier in Portland Metropolitan transportation network. First, we create two scenarios based on a tiered structure identified by CH2MHILL (2012). To better demonstrate the impact of bridge failure on travel time, Oregon Department of Transportation (ODOT) and Portland International Airport (PDX) are selected as origin and destination, respectively. Therefore, two different scenarios with opposite sequence are developed and presented in Table 1.

As shown in Figure 2(a), two scenarios displayed similar patterns despite the different failure sequence. The travel time is increasing when the number of failed bridges grows. Not only on the specific route (from ODOT to PDX), but also mean travel time over the network also exhibits the similar trend. The proposed two scenarios indicate that travel time is slightly influenced by bridges' failure sequence, but more significantly, with the number of the failed bridges. To validate our argument, a Monte Carlo simulation is conducted as in Figure 2(b). In each case, 5 random scenarios are identified and simulated. Their mean travel time is then calculated and plotted. Similarly, Monte Carlo simulation suggests the number of bridges failure contributes more to the travel time change, which further validated our argument. From the network resiliency perspective, the results can be interpreted as the Portland transportation network is resilient to bridge damages. Small travel time variation between one failed bridge and five failed bridges indicates that, although the bridge failure caused the loss of capacity, the network is able to adapt the disruption without severely deterioration in the travel time performance.

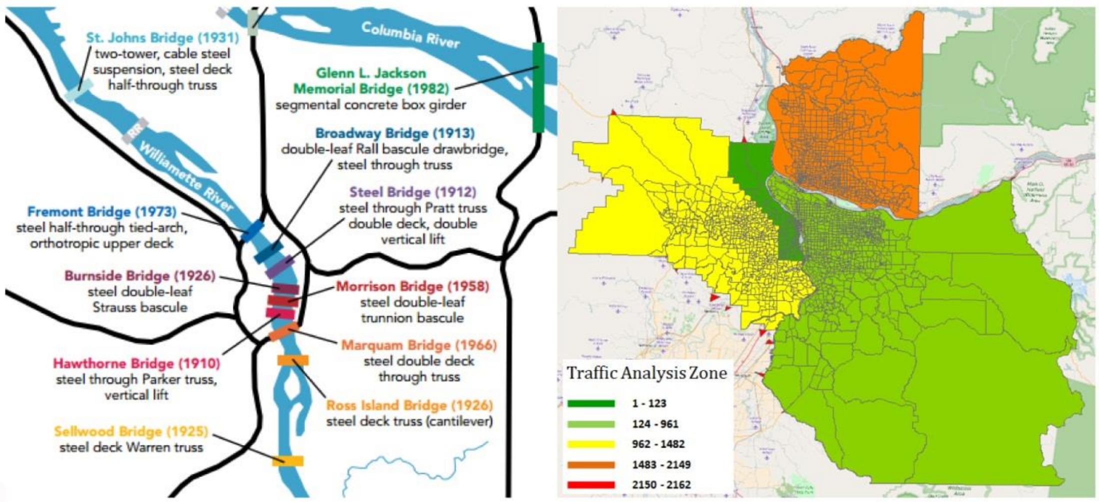



**Figure 1. Study area Portland, Oregon. (a) Bridge locations (Talbot, 2012) (b) Traffic analysis zone assignment.**

**Table 1. Investigation Scenario.**

| | Bridge damage sequence |
|---|---|
| Scenario 1 | Broadway, Steel, Burnside, Morrison, Hawthorne, Ross, Fremont, Marquam |
| Scenario 2 | Marquam, Fremont, Ross, Hawthorne, Morrison, Burnside, Steel, Broadway |

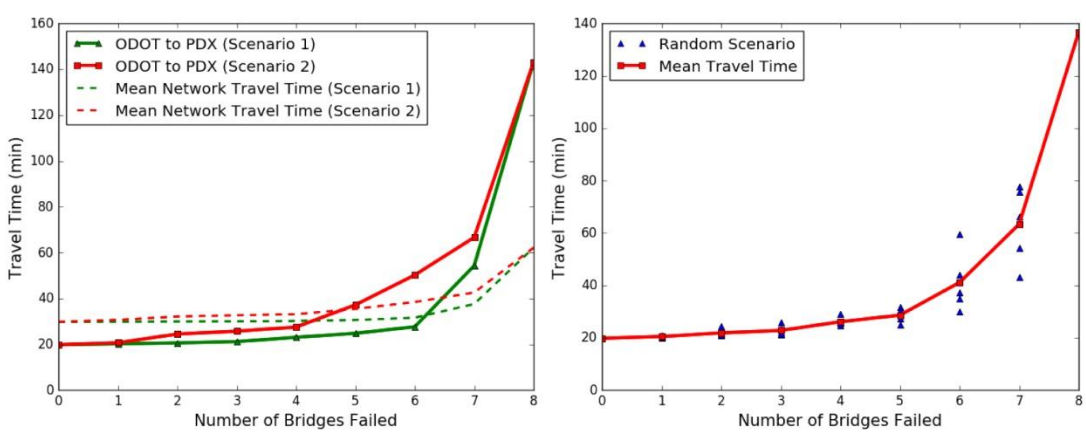



**Figure 2. (a)Travel Time under different bridge failure scenarios (b) Monte Carlo Simulation.**

**Bridge Rating through Travel Time Contribution:** Comparing the scenario that seven out of eight bridges are failed and the case that all of them are failed, the travel time difference can be used to measure the surviving bridge's contribution to the network. Therefore, a travel time sensitivity analysis can be conducted based on different last-bridge-functioning cases. As shown in Figure 3, failure of Fremont and Marquam Bridge lead to a greater increase of travel time than other bridges. This finding is validated by the location of two bridges. Fremont locates on I-405 while Marquam locates on I-5, they are both vital freeways that carry the major traffic flow on the network. Therefore, the failure of these two bridges is expecting to lead to an increase of the overall travel time. The rank of the bridges can be further concluded from Figure 3 as Fremont, Marquam, Morrison, Burnside, Broadway, Steel, Hawthorne, and Ross. This rating provides us a new perspective in prioritizing the bridge retrofitting.

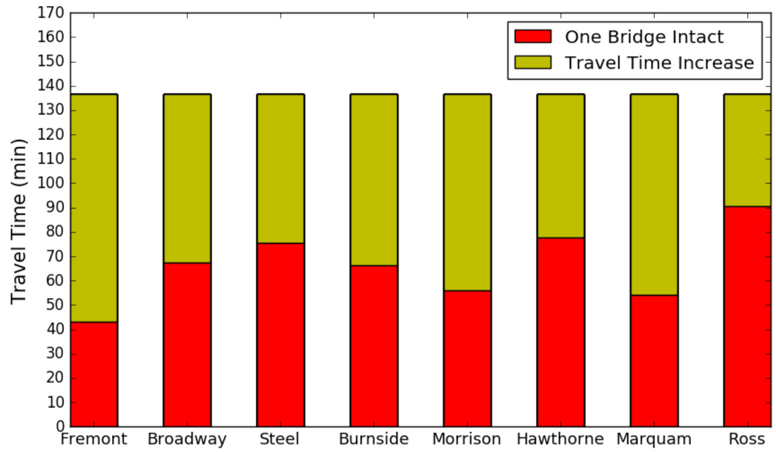
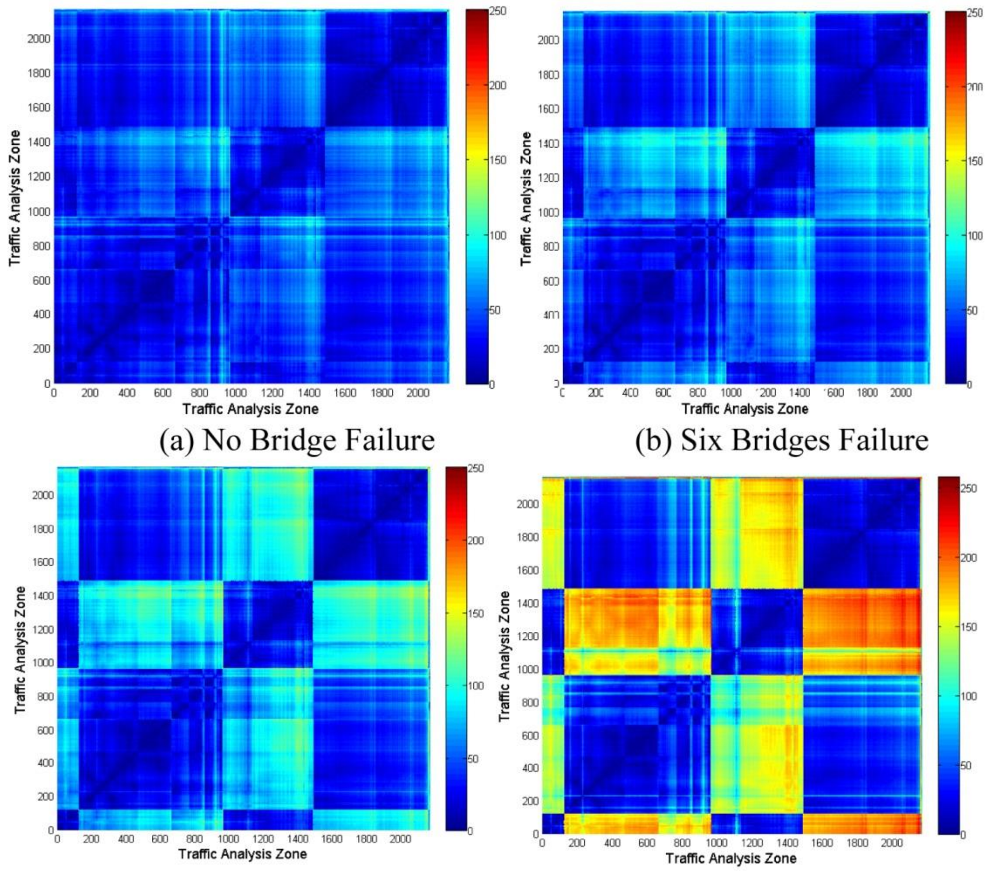



**Figure 3. Sensitivity Analysis.**

**Network Wide Travel Time:** Instead of focusing on a specific Origin-Destination (OD) pair, zone to zone travel time over the network is calculated and presented in Figure 4. The increase of the travel time over the network can be visualized from the heat map in Figure 1(b) as the number of failed bridges increase. In Portland network, 2,162 TAZs are categorized into four sections, zones 1-123 and 962-1,482, which are located on the west side of the river, and zones 124-961 and 1483-2149 located on the east side. The highlighted blocks are travel time of the pair zones that are on the opposite sides of the river. When a bridge is destroyed, the traveler will reroute to another bridge. It leads to the travel time increase by adding the travel time due to rerouting and delay caused by concentration of traffic and resultant congestion. Coincide with Figure 2(b), travel time does not change dramatically till the number of failed bridges reaches six. This supports our argument in section 4.1 that the investigated transportation network is resilient for a moderate scale of disruption. However, if a M9.0 Cascadia Subduction Zone (CSZ) earthquake occurs as evaluated in the Oregon Resilience Plan (ORP) (Madin and Burns, 2013; OSSPAC, 2013), most of the bridges will be closed. The network travel time presented in this study will be helpful in facilitating the transportation emergency response development.

## SUMMARY AND FUTURE REMARKS

In this paper, bridges' impact on transportation network performance, i.e. travel time, is studied. Different scenarios were developed for the study site, Portland, OR. Eight bridges over the Willamette river were primarily focus of this study. First, travel time from ODOT to PDX is investigated through two different bridge failure scenarios. Validated by Monte Carlo Simulations, the result suggested that the transportation is resilient to the minor damage till the bridge failure escalates. In addition, we developed the scenario to prioritize the bridges. Between the cases that only one bridge and no bridge is functioning, the travel time is calculated. The contribution to the travel time increase indicates the bridge's significance level to the network performance. Therefore, a rating list of bridges based on travel is generated.




(a) No Bridge Failure (b) Six Bridges Failure

(c) Seven Bridge Failure (d) Eight Bridges Failure

**Figure 4. Zone to Zone travel time with different bridge failure scenarios.**

Finally, zone to zone travel times under different bridge failure scenarios are inspected. The heat map indicates that cross-river travel times increase as the number of failed bridges increase. The change is obvious when the accumulated failed bridges reach six. In the future research, the probability of link damage would be incorporated. In addition, since the failure is randomly placed on the network, a stochastic approach will better characterize the network disruption process. Furthermore, instead of assuming the complete failure of the bridge, different percentages of link capacity reduction will be considered.

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