METHODOLOGIES FOR SIMPLIFIED LIFELINE SYSTEM RISK ASSESSMENTS

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ABSTRACT

Methodologies for Simplified Lifeline System Risk Assessments

Michael Germeraad

Natural hazards are a growing risk across the globe. As regions have urbanized, single events impact greater proportions of the population, and the populations within those regions have become more dependent on infrastructure systems. Regional resilience has become closely tied to the performance of infrastructure. For a comprehensive risk assessment losses caused by lifeline outage must be considered alongside structural and nonstructural risks. Many well developed techniques quantify structural and nonstructural risk; however, there are insufficient procedures to determine the likelihood of lifeline outages. Including lifelines in seismic assessments will provide a comprehensive risk, improving a decision maker's capacity to efficiently balance mitigation against the full spectrum of risks.

An ideal lifeline risk assessment is infeasible due to the large geographic scale of lifeline systems and their system structure; these same characteristics also make them vulnerable to disruption in hazard events. Probabilistic methods provide solutions for their analysis, but many of the necessary analysis variables remain unknown. Continued research and increased collection of infrastructure data may improve the ability of advanced probabilistic methods to study and forecast performance of lifelines, but many inputs for a complete probabilistic model are likely to remain unknown. This thesis recognizes these barriers to assessment and proposes a methodology that uses consequences to simplify analysis of lifeline systems.

Risk is often defined as the product of probability of failure and consequence. Many assessments study the probability of failure and then consider the consequence. This thesis proposes the opposite, studying consequence first. In a theoretical model where all information is available the difference in approach is irrelevant; the results are the same regardless of order. In the real world however, studying consequence first provides an opportunity to simplify the system assessment. The proposed methodology starts with stakeholders defining consequences that constitute ruin, and then the lifeline system is examined and simplified to components that can produce such consequences. Previously large and expansive systems can be greatly simplified and made more approachable systems to study.

The simplified methodology does not result in a comprehensive risk assessment, rather it provides an abbreviated risk profile of catastrophic risk; risk that constitutes ruin. By providing an assessment of only catastrophic lifeline risk, the risk of greatest importance is measured, while smaller recoverable risk remains unknown. This methodology aligns itself with the principle of resilience, the ability to withstand shocks and rebound. Assessments can be used directly to consider mitigation options that directly address stakeholder resilience. Many of the same probabilistic issues remain, but by simplifying the process, abbreviated lifelines assessments are more feasible providing stakeholders with information to make decisions in an environment that currently is largely unknown.

Keywords: Lifelines, Risk Assessment, Resilience, Hazards, Earthquake Engineering

ACKNOWLEDGEMENTS

"There is an opportunity for each discipline to reciprocally advance the other where collective discoveries emerge beyond any single field." – Robert Full

This thesis was framed with an understanding of barriers that exist in the real world. Approaching the problem from solely an engineering perspective would have resulted in an entirely different methodology. The foundation of this thesis required the blending of resilience planning with engineering

First and foremost I have to thank my thesis advisor Dr. Robb Moss. I called him blindly when I was exploring graduate schools and expressed my interest in combining earthquake engineering with hazards planning. Since then we've shared many conversations about how to improve work in the real world recognizing present barriers. This thesis has gone through many large edits and has been influenced by a number of different side projects we have worked on together. I'm thankful for his guidance when the research was disorganized, and his encouragement in tackling such an expansive topic. Thank you, and I look forward to continually working with you on all things hazards.

The work of my committee in the final month of preparation was invaluable in polishing what was a very rough product. Ken Topping and Dr. Charles Chadwell provided strong perspectives from the hazards planning and earthquake engineering fields, providing me with a sounding board of unique expertise. I have to also thank larger groups of the Cal Poly Staff that allowed me the opportunity to work on two State documents that helped ground my research. Dr. Adrienne Greve and the California Adaptation Planning team along with Dr. David Conn and the State Hazard Mitigation Plan team were both groups that provided me an opportunity to spend greater time on my research.

Similarly while writing the bulk of the thesis I had the opportunity to work with the Association of Bay Area governments on a document that was a direct application of my thesis. This opportunity was invaluable to keep my focus on the topic, and introduced challenges that were previously not considered. I'm grateful to the staff who gave me freedom to approach issues from a new and unpolished methodology.

I have to thank the Earthquake Engineering Research Institute and its members. The EERI community has been an invaluable resource for a young researcher to tap into with its vast library of information and more importantly its active membership. I've gained so much through sidebar conversations at conferences, meetings, and in the office. Thank you to everyone who I've talked with over the past few years.

Lastly, and most importantly is my family. This thesis has been a part of me for three years. You've always taken an interest in my research. The support you've given throughout my life has always allowed me the opportunity to focus on my education. Thank you.

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1 INTRODUCTION

"Nature always bats last." – Paul Ehrlich

Natural forces occur over millennia as climates cycle, and continents slowly divide and collide. These forces that lift mountains and carve river systems can at times release massive amounts of energy in brief moments which can be disastrous when they interact with urban environments. While lessons are often learned from past earthquakes, society's development continues to present new complexities never experienced previously. Neighborhoods look and function differently today than they did a century ago. During this century of rapid development, only a handful of earthquakes have occurred, resulting in a continued earthquake risk despite many past improvements.

In seismically advanced regions of the world science, engineering, and policy adopted by the earthquake community have decreased life loss. Despite these improvements, earthquakes remain disastrous due to their economic and social impact. Over the past century regions have urbanized and in the process become more reliant on infrastructure. While life safety will remain a policy priority, neighborhood resilience and business interruption have become significant issues to address.

> *"Tremendous efforts concentrated on upgrading seismic safety have realized urban regions relatively safer than what they were before. This has made us observe cases in moderate earthquakes where lifeline systems are disrupted and greatly affect urban functions even when the safety issue is not thrown into catastrophic danger. This means that improvements in seismic safety have increased the importance of seismic reliability issue. These factors have led to*

the birth of a new branch of earthquake engineering called lifeline earthquake engineering," (Kameda, 2000)

Modern urban societies are more dependent on infrastructure systems than they used to be. These infrastructure systems, critical for social and economic functions, have been coined lifelines. Lifelines, illustrated in Figure 1.1, are the systems relied on by the majority of developed society. Lifelines are defined in the literature as:

"Several utilities [are] termed lifelines, because of their crucial role in sustaining social and economic systems and because of their network characteristics, which make them especially vulnerable to disruption from natural disasters," (Rose et al. 1997).

"Lifeline systems include energy (oil, electric power, natural gas), water and wastewater, transportation (air, land, sea modes), and communication networks. These are typically but not exclusively geographically distributed. Lifeline systems typically have sources, transmission systems, and distribution systems," *(*Taylor & VanMarcke, *2002).*

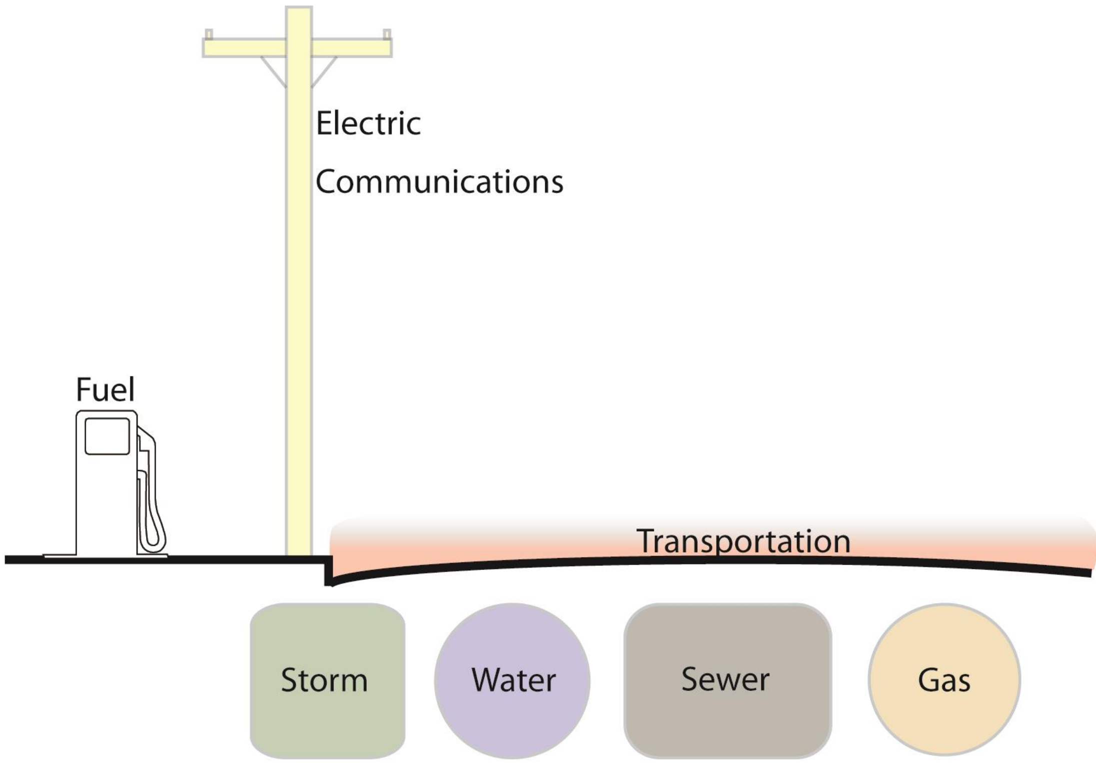


Figure 1.1: Lifeline Systems.

Functioning lifelines are necessary for everyday activities. Annual outages caused by winter storms are reminders of personal and business reliance on critical infrastructure. In small events systems are disrupted for hours or are isolated to a single system making the outage manageable for most. In large earthquake events outages can last days, weeks, and months and occur across multiple lifelines.

Reliance on lifelines is important in typical conditions but they become vital during disaster response. The consequences of a single event can lead to a complex cascade of related incidents, expanding beyond systems or stakeholders directly affected by the initial event (Oliveira Roca & Goula, 2006). Disruptions to communications, water, and transportation networks cause initial emergencies to cascade into disasters. A

swift response to fires or hazardous releases limits additional damage following the initial event. Access to lifelines following an event has a significant impact on the ability of a region to quickly respond and contain an event. Lifelines also play a large role in recovery.

The functionality of most homes and businesses following an earthquake is governed by either facility damage (structural and nonstructural), or lifeline failure. For the majority of organizations lifeline outage is likely to be the governing cause for closure. In 1993, Midwest floods resulted in both facility and lifeline damage for businesses in Des Moines, Iowa. In a survey "data indicated that actual flooding was a comparatively rare source of business disruption in Des Moines, and that the loss of critical lifeline services, particularly water, was a much more important cause of business closure, affecting a significantly larger number of businesses," (Tierney & Nigg, 1995). While this represents outcomes from a flood, the relationship between facility damage versus lifeline outage losses is similar across all hazards. Often in disasters the hallmark images are of structural damage to a home or facility, but for most, lifeline outage is the governing recovery variable. Figure 1.2 outlines a more complete portfolio of organizational risk. The words may change slightly, but the same schematic can also outline the probability of a habitable home.

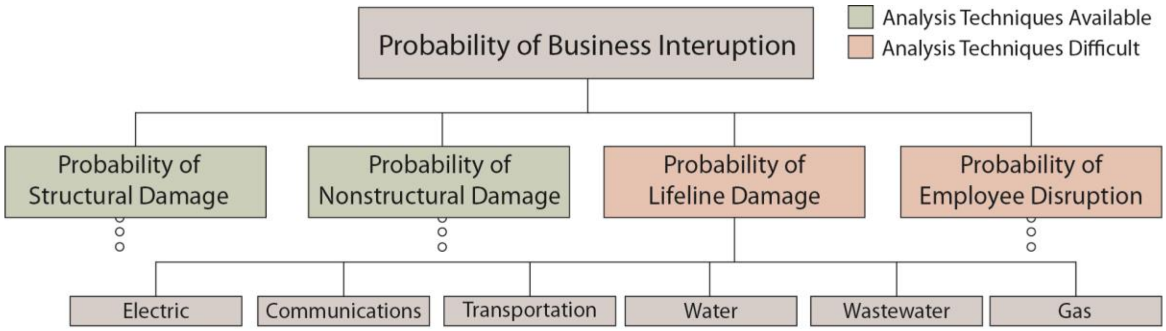


Figure 1.2: Causes of Business Interruption.

There are many well developed techniques to quantify the risk of structural and nonstructural damage due to seismic loadings (ASCE-41, FEMA E-74); however, there are insufficient procedures to determine the likelihood of lifeline outage. When the risk is unknown lifeline mitigation projects are difficult to advocate for. Without an understanding of the existing risk there is no baseline for predicting the benefits of mitigation. A methodology to analyze and quantify the risk will aid decision making for both lifeline operators and users. With information infrastructure providers may implement mitigation projects, and individuals and institutions may choose to increase internal capacity to limit losses in future disasters, together preventing catastrophes caused by long lifeline outages.

1.1 Framework for Lifeline Risk Analysis

An ideal risk assessment is infeasible due to the scale of lifeline systems and a number of variables that influence system performance. This thesis proposes an abbreviated assessment that focuses analysis on catastrophic risk. Stakeholders prioritize which lifelines are most important, the relationships between them, and which outage

lengths are acceptable for each system. This organizes the risk probabilistically and bounds the assessment on system elements that govern longer restorations that cause catastrophic losses.

For individuals and regions to effectively mitigate risk they first must know what the risk is. Risk is commonly calculated as:

$$Risk = [Probability\ of\ Failure] \times [Consequence] \qquad \textbf{EQ 1.1}$$

However, in most cases there are multiple degrees of failure, each resulting in a unique consequence. For lifelines both the length of outage and level of service will dictate the consequence. The equation then becomes:

$$Risk\ Profile = \sum_{x=1}^{n} [Probability\ of\ Outage\ x] \times [Consequence|x] \qquad \textbf{EQ 1.2}$$

$$where\ x\ is\ the\ outage\ length$$

The overall risk is a summation of the product of each outage length and the resulting consequence. In a theoretical environment where both variables are known the risk can be plotted as in Figure 1.3. In the figure the blue line represents the probability of a certain outage length, and the red line represents the increasing consequence as the outage length time increase. Their product is displayed by purple columns. Despite the high probability for small outages in this theoretical risk profile, it is the high consequence, low probability events, which produce the greatest risk. With this information users can then make preparedness decisions based on the risk. Some preparedness measures may reduce consequences across all outage lengths while others may lower consequences for a limited time. Storage of resources (power, water, fuel, etc.) lasts for a finite period from the start of the outage until storage runs out. Other

solutions like a mobile workforce with telecommuting capabilities may initially be out for the first week while communications systems are repaired but may then become effective in the following weeks while transportation networks undergo longer repairs. With this distribution an organization can make educated mitigation or preparedness decisions to minimize losses for certain outage events.

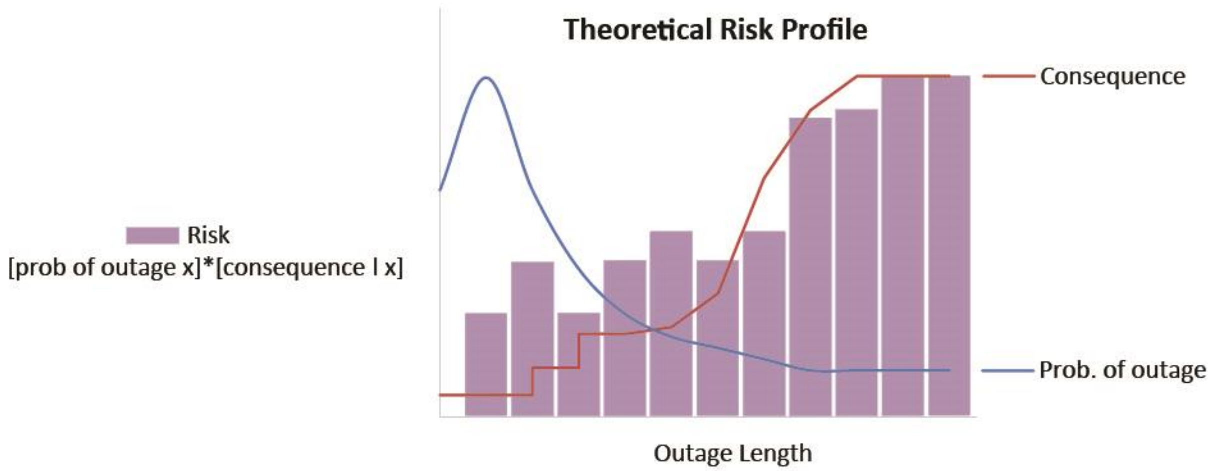


Figure 1.3: A Theoretical Risk Profile.

In practice however, it is difficult to accurately develop the probability of outage. Alternatively, this process can work backwards. Rather than providing users with a comprehensive risk profile users may help to simplify the problem by focusing the analysis on specific outages. The problem then changes to become:

$$Abbreviated\ Risk\ Profile = \sum_{x=c}^{n} [Probability\ of\ Outage\ x] \times [Consequence|x] \quad \textbf{EQ 1.3}$$

$$where\ c\ is\ the\ outage\ of\ concern\ for\ an\ organization\ or\ region.$$

This methodology simplifies system probability analysis. Analysis is focused on scenarios and system elements that govern long outage scenarios.

Only system components that greatly impact the system performance remain as variables in system performance. The larger c is, the fewer variables that exist. If an organization sets c as 3 hours few simplifications can be made; however, if c is set to 3 days or 3 weeks, the system can be significantly simplified to only include components that will govern a longer outage. Figure 1.4 illustrates the masking of outage lengths less than c, leaving an assessment that only focuses on the probability of long outages and high consequences.

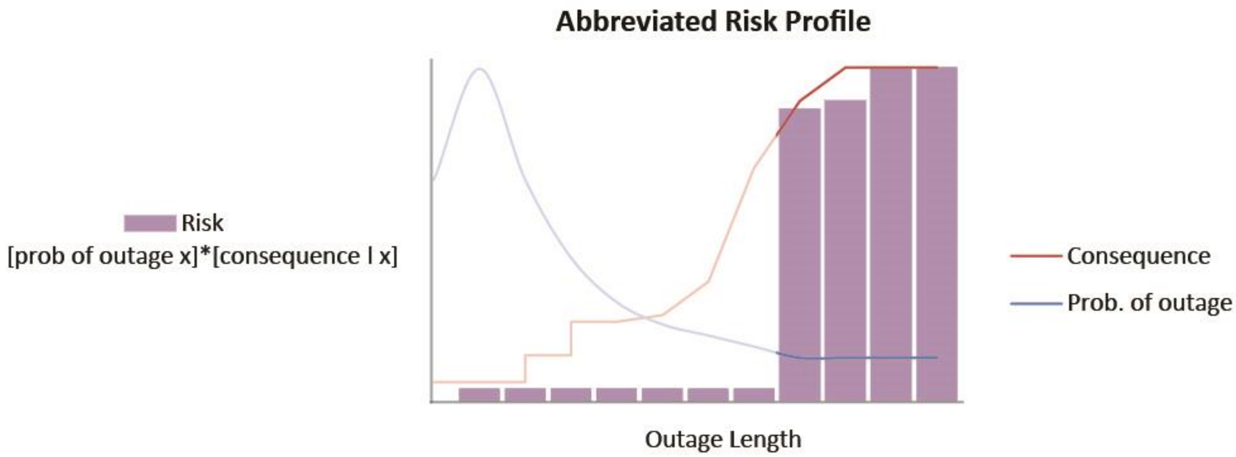


Figure 1.4: An Abbreviated Risk Profile.

1.2 Introduction Summary

For a comprehensive risk assessment lifelines must be considered alongside structural and nonstructural risks. Including lifelines in seismic assessments improves decision making capacity to balance mitigation against the full spectrum of potential consequences. An ideal risk profile is infeasible due to the scale of lifeline systems and the number of variables that influence system performance. An abbreviated risk profile

simplifies analysis by bounding the assessment on system elements that govern longer restorations that cause catastrophic losses, providing both infrastructure providers and users with a resource to properly mitigate and prepare.

While admittedly there are a number of assumptions and unworked theories with the proposed methodology, it is important to remember that lifelines and hazards pose a problem that has no perfect answer. Solutions are gauged by better and worse rather than correct and incorrect. Uncertainty, a lack of data, multiple stakeholders, and system probability complexities will continually cloud lifeline risk assessments. Even with a simplified system, these problems persist. These barriers are explored in the thesis in an effort to better understand the relationships of each variable on system performance to further simplify the assessment on governing variables. The methodology offers a feasible solution to characterize catastrophic lifeline risk, providing insight into the risk that most directly threatens the greater resilience of those that operate and rely on lifeline systems.

2 LITERATURE REVIEW

"For wicked problems there is no solution that can be shown to be optimal…because the system is constantly subject to unanticipated change, the idea of a best solution is a mirage." –Judith Innes

Lifelines are complex systems with multiple factors that influence their overall performance. Addressing the main variables provides a foundation to analyze lifelines implicitly at a high level. This chapter provides an overview of past lifeline seismic vulnerabilities and introduces concepts that are necessary for system probability analysis.

2.1 Earthquake Case Histories

In past earthquakes system characteristics have been exposed when lifelines and hazards interact. While there are valuable lessons in other earthquakes, Loma Prieta (1989), Northridge (1994), Kobe (1995), Maule - Chile (2010), and Christchurch (2011) will be used to highlight lifeline failures, successes, and their consequences on society. These earthquakes were chosen due to similarity in infrastructure stock, and design/construction standards. Other non-earthquake events are included in Appendix A in the case histories portion of the State Hazard Mitigation Plan Lifeline Annex (http://hazardmitigation.calema.ca.gov/docs/SHMP_2013_Annexes1-6.pdf). Concepts introduced by the case studies will be discussed individually in greater detail in section 2.3.

2.1.1 Loma Prieta, CA

In 1989 a M 6.9 earthquake (USGS, 2012a) 60 miles south of San Francisco killed 62, injured 3,757, and caused more than $7 billion in losses (EERI, 1990). The Loma Prieta Earthquake was a large event, but was located a far enough distance from the San Francisco Bay Area that it caused substantially less damage than if it were a "direct hit". Nonetheless there were a number of failures from this event that warrant careful attention. Lifeline damage included the Bay Bridge failure, Cypress Viaduct collapse, Highway 17 closure, and the failure of San Francisco's high pressure auxiliary firefighting water system.

In the Loma Prieta earthquake ground shaking and liquefaction in the Marina District of San Francisco caused widespread damage to wood frame residential structures. Gas mains into these structure ruptured, which sparked a fire that quickly spread. Fire crews arrived on the scene only to find that the water suppression system had failed and no water pressure was available to put out fires. The City of San Francisco has a 135 mile "seismically resistant" auxiliary water suppression system (AWSS) consisting of distributed large cisterns to provide scattered water sources across the city without relying on long stretches of pipeline. The system is independent of potable water system and is used for firefighting.

In the earthquake a 12 inch main of the AWSS had failed and six fire hydrants were damaged by soil deformations in the area south of Market. It is estimated that this drained the 750,000-gallon Jones Street tank in about 20 minutes; the tank that would have been used to extinguish the fires in the Marina District (Schiff, 1990). Air entered the nearest pumping station, further preventing water from reaching the fire. Two

fortunate events limited the potential damage due to fire; 1) calm winds, and 2) availability of the (soon to be decommission) fire boats. The fire department was in the process of selling off the fire boats because there was full reliance on the “seismically resistant” water distribution system. The redundancy of the fire boats provided the independent backup system needed to suppress the fires. In other portions of the city AWSS and the municipal water supply were interrupted by power outages. Power loss prevented remotely controlled isolation valves on the AWSS from operating. As is typical, interdependency between lifelines resulted in the loss of undamaged, operable systems. Other systems that hampered firefighting were overloaded telephone lines preventing fires from being promptly reported. The separate fire department radio communications was also encumbered by the high volume of calls.

It may appear to be bad luck that the AWSS system failed in an area that had fires (as the majority of AWSS performed well), but it was not random. AWSS and the gas lines failed due to local ground shaking and deformations. Assessing the correlation between lifeline elements is critical when developing an accurate risk profile. Correlation is a variable that quantifies one event’s influence on another. Without correlation, the broken gas and water pipeline would be independent of each other and failure would be unlikely to occur at the same place; however, with correlation the likelihood of both systems failing near one another is highly possible.

The transportation system in the greater Bay Area sustained 1.8 billion dollars in damage due to the earthquake (Comerio, 1998). The most prominent failures were the collapse of the Bay Bridge deck, collapse of the Cypress Viaduct in Oakland, and the closure of Highway 17. Before the earthquake, the heavily trafficked Bay Bridge

corridor carried 254,400 vehicles daily (Yashinsky, 1998) and was closed to traffic for a month to repair the deck damage. To offset the loss of this bay crossing, alternative corridors and alternative means of transportation provided the redundancy needed to maintain some functionality. Bay Area Rapid Transit (BART) initiated 24-hour daily service and increased its ridership from 218,000 daily passengers to 357,000 passengers, a 64% increase (Schiff, 1990). Alternate bridges across the bay saw both general and freight traffic increase. The Golden Gate Bridge had its busiest day in history ten days after the earthquake.

Twelve miles of Highway 17, another key corridor connecting Santa Cruz and Santa Clara counties, were closed due to earthquake and landslide damage. The corridor, the only multi-lane highway between the two counties, was closed or restricted for 32 days (Schiff, 1990). The closure of Highway 17 impacted travel in between Santa Cruz and Santa Clara counties but also impacted rail commuters on the peninsula between Gilroy and San Francisco. Caltrain, a three county passenger rail system, had no track damage, but had employee disruptions. Many Caltrain crew members lived in Santa Cruz and could not travel to work due to damaged roads (Schiff, 1990). The Santa Cruz/Santa Clara transportation corridor was solely reliant on Highway 17. In comparison, the Bay Bridge closure had dramatic travel impacts, but BART, ferries, and alternate bridges provided alternative commute options, demonstrating a redundant system.

2.1.2 Northridge, CA

In January 1994 the M 6.7 Northridge earthquake rattled Southern California. There were no catastrophic failures in the power, water, wastewater, communication and gas transmission systems. The transportation network did have considerable damage which limited hospital access in the epicenter region. In the Los Angeles region there are 27 freeways totaling 615 miles of roadway (Leung, Yee & Wesemann, 1995). Over 1,200 bridges experienced accelerations greater than 0.25g, seven sustaining severe damage, and another 230 experiencing minor damage (Yashinsky, 1995). Damage at the interchange between Interstate 5 and State Route 14 caused closures and considerable delays for both corridors. These routes handle significant amounts of the freight traffic and commodities' movements north out of Los Angeles. Shipping companies were quick to react, with 30 to 50 percent of all Los Angeles truck trips immediately canceled before lengthy detours across other State Routes were in place. Accelerated repair design, execution of emergency contracts, cooperation among agencies, and detours quickly restored access, limited delays, and accelerated the rebuilding process. By May, just four months after the earthquake, $122 million had been spent on highway repairs and $144 million on bridges (Yashinsky, 1995). In November, ten months later, all highways impacted by Northridge were open to traffic.

At the time of the earthquake Los Angeles Department of Water and Power (LADWP) serviced 4.1 million people and had 712,000 water service connections. Initially 670,000 residents were without water and another 180,000 had reduced pressure. Table 2.1 summarizes the damage. The system was completely operable 12 days after the event supplying customers pre-disaster service despite only repairing 8/60

transmission line leaks. LA Water restored functionality 6-9 years after the earthquake (Davis, 2013). Two weeks after the earthquake the water system was operable, but was not functioning at its pre-earthquake reliability. For the purposes of community resilience operability is important, for system resilience functionality is necessary (Davis, 2013). Recognizing the difference is important for clear communication and when prioritizing mitigation prior to the event or prioritizing work during response and recovery.

Table 2.1: Northridge Damage to LA Water System

Damaged Component	Quantity
Raw Water Pipes	14
Transmission Pipes	60
Distribution Pipes	1013
Service Connections	200
Reservoirs	7
Treatment Plant	0.5
Lost Power up to 27 hours	-

Davis, 2013

2.1.3 Kobe, Japan

Exactly one year to the day after the Northridge earthquake, a M 6.9 earthquake resulted in 6,300 deaths and caused $200 billion in losses in the Hanshin region of Japan (Schiff, 1998). "In contrast to the 1994 Northridge earthquake, which was a moderate-sized disaster, the Kobe earthquake represented the industrialized world's first experience of a catastrophic urban earthquake disaster," (Chang, 2000). Kobe, a port city of 1.5 million people, incurred the majority of the regional damage. Liquefaction at the port resulted in $10 billion dollars of damage. Despite rapid reconstruction repairs were not

completed until March 1997, two years after the earthquake. During the two years of reconstruction the Port dropped from its pre-earthquake ranking of 6^{th} to 17^{th} (Chang, 2000). During reconstruction the port dropped as low as 24th. In addition to the losses incurred at the port, related port operations represented 17% of the local employment. The losses in business and income accounted for over $4 billion in just the 9 months following the earthquake. A study found that soil improvement mitigation would have had a high investment return at the Port of Kobe. The rate of return given the year of the earthquake would have resulted in a 22% rate of return had soil improvements been included in port construction (Werner, Dickenson & Taylor, 1997). A sensitivity study showed that had the earthquake occurred earlier the return would have been much higher, and if the earthquake had occurred later, the return would have been comparable. A few berths at the port of Kobe were seismically designed and performed well and were used for emergency relief during the earthquake response (Chang, 2000).

Ports and airports are included in lifeline studies as they are key nodes in transportation networks. The Kobe Port internally incurred large losses due to the earthquake, but the businesses that relied on shipping also shared substantial losses. The Kobe earthquake is not a unique scenario. Ports in Seattle, Tacoma, Oakland, Los Angeles, and Long Beach all are in seismic regions capable of similar or larger earthquakes. These ports not only have direct ties to their regions, but are responsible for large portions of their state's and the nation's goods movement. Five of the seven largest North American container ship ports are in seismically active regions, capable of producing catastrophic earthquakes, see 2011 container port rankings in Table 2.2.

Table 2.2: North America Port Container Traffic in Seismic Regions.

2011 Rank	Port	Containers
1	Los Angeles, CA	7,941,000
2	Long Beach, CA	6,061,000
5	Vancouver, British Columbia	2,507,000
6	Oakland, CA	2,343,000
7	Seattle, WA	2,034,000
11	Tacoma, WA	1,485,617

(AAPA, 2012)

The severity of the Kobe earthquake resulted in long lifeline outages. Complete restoration took 7 days for electricity, 82 days for water, 85 days for natural gas, 6 months for major rail lines, and 20 months for highway bridges (Kameda, 2000). The water system alone had 134,000 service and 3,600 distribution mains break in the earthquake. High performance pipelines performed well even in areas of liquefaction and large permanent ground deformation, but older more brittle pipes resulted in wide spread failures. It took two weeks to return water service to half the customers and 40 days to return service to 90 percent of customers. Figure 2.1 shows the recovery of the Kobe earthquake and other urban earthquakes similar in magnitude to the 1994 Kobe earthquake.

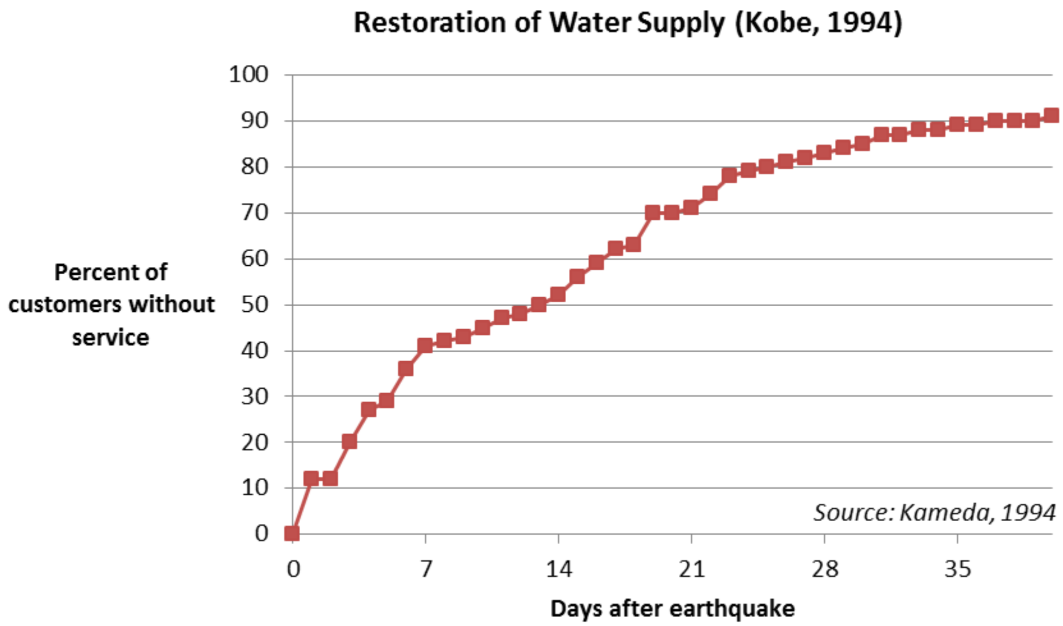


Figure 2.1: Water Supply Restoration of 1994 Kobe Earthquake.

2.1.4 Maule, Chile

The 2010 M8.8 Maule Earthquake was an earthquake that affected a vast region of Central Chile, with 72% of Chile's population experiencing MMI VII or stronger intensity shaking (EERI, 2010). At the time it was the 5th largest earthquake recorded since 1900. Although the epicenter was 210 miles away from Santiago, the ground shaking had a large impact on the city. The electric grid went down throughout most of Central Chile including metropolitan Santiago a region of 6.1 million people. The loss of power precipitated the loss of communication in the form of radio, television, telephone, cell phone, internet, and others. The loss of power also brought to a halt the water distribution in Santiago that relies on electric pumps. This lack of services presented an inconvenience to some, a risk to other more vulnerable populations, and a hindrance to

disaster recovery particularly because Santiago is the seat of power for the country. The interconnectedness of the power, communication, and water is an obvious concept but difficult to untangle for ensuring resiliency.

Closer to the epicenter is the city of Concepcion, population 900,000. Here not only was power and water out, but all communication to the city was severed. The city was isolated and had no means of communicating with the rest of the country or receiving word that help was on the way. The lack of information compounded the lack of essential services and resulted in a break in the social fabric of that community. The government was absent and did not communicate with people in Concepcion; "many officials believed that looting became more widespread due to a delay in mobilizing the army to assist with local law enforcement and security. When the military began to arrive more than 48 hours after the event, the looting quickly subsided," (American Red Cross, 2011). Once communication was restored the civil unease dissipated and recovery and reconstruction began. The initial power outage was a major cause of the communication network interruption, which then aggravated the social unrest in Concepcion.

Water in Concepcion was severely disrupted. The water treatment facility that serviced 300,000 residents came close to losing its only water intake pumps. The one building responsible for the water pumping in the region was a seismically vulnerable building that suffered major damage. Had the pumps been damaged it could have required months to have them replaced by an overseas vendor (ESSBIO, 2010). After the main shock temporary steel cages were constructed to protect the pumps in the case of further building collapse in future aftershocks (see Figure 2.2).

Figure 2.2: Temporary Protection of Water Intake Pumps in Concepcion Chile.

Even with the intake pumps operational, pipeline breaks limited service to only 17% of the population a day after the event. In an August 2010 presentation ESSBIO, the water provider, listed 4 main barriers to restoration:

- No power supply in most of the main water and sewage plants.
- Although the plants have power generators the lack of oil supply was a major problem. Fuel was also unavailable for contractor vehicles.
- The collapse of the public telecommunications networks impeded the coordination among personnel, with suppliers and contractors.
- In the first few days looting in supermarkets, oil stations, banks and retail stores affected the logistics for a proper response to the emergencies causing a security problem for personnel.

ESSBIO, was initially very slow to begin repairs due to civil unrest and limited telecommunications. ESSBIO requested electrical service priority to key facilities and also asked for military security in areas of safety concern. When these barriers were removed restoration was quite rapid. The water system restoration is shown in Figure 2.3

and compared against the water restoration following the 1994 Kobe earthquake. In Chile, after slow start, the repair efforts quickly surpassed Kobe's restoration. It took five weeks to return service to 90% of residents. During this time of limited service ESSBIO deployed 900 portable water tanks to provide residents with the water needed to survive during the water outage (ESSBIO, 2010).

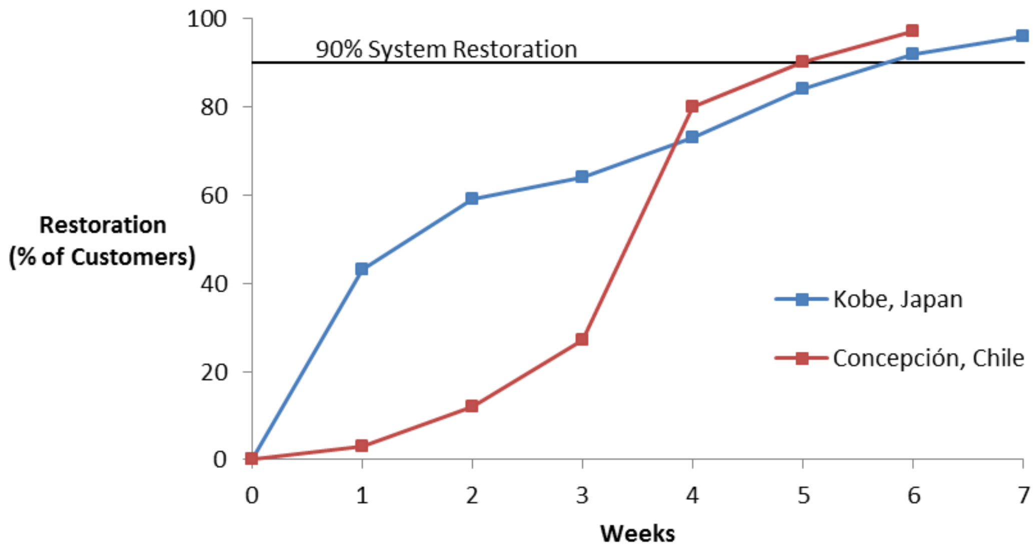


Figure 2.3: Water Restoration in 1994 Kobe and 2010 Chile Earthquakes.

The main highway that runs North-South in Chile is Routa 5. Ground shaking and/or liquefaction resulted in widespread damage to this transportation artery slowing relief efforts, reconstruction, and regular commerce. The damage occurred generally due to two types of failures (GEER, 2010). The first was foundation soil failure at small water crossings. The major water crossings were engineered with well-designed bridges and abutments, but the lesser crossings were not addressed with the same engineering rigor and often failed, sometimes catastrophically, taking out large sections of the four lane highway. The second failure mode was small, but ubiquitous deformations of the

engineered abutments throughout the affected region (Schanack, Valdebenito & Jorge, 2012). In this case a few centimeters of settlement of a bridge abutment in the approach to a bridge necessitated a slowing of traffic. This was observed at over 100 bridges. The failures were not catastrophic but nonetheless the pervasive damage was costly to fix because of the large number of bridges needing attention.

Chile's two largest oil refineries (130,000 and 98,000 barrels per day) were shut down following the earthquake due to power outages and to assess possible damage and check critical elements (TCLEE, 2010). The smaller of the two located near Santiago had minor damage and resumed production ten days after the event. The larger refinery in the Biobío region had equipment displaced and pipeline damage. One of two crude pipelines that feed into the facility was damaged by lateral spreading along the shore. Despite being classified as minor damage initial assessments estimated full operation would not be restored for three to seven months (TCLEE, 2010).

2.1.5 Christchurch, New Zealand

In February 2011 Christchurch experienced a M6.3 earthquake directly under the city resulting in over $20 billion in damages and 185 casualties. The region experienced a larger M7.1 earthquake less than six months earlier, which had caused $4-5 billion in damage (EERI, 2013). Among many failures, the February 2011 quake resulted in extensive damage to distribution infrastructure in neighborhoods severely affected by liquefaction. In some cases whole neighborhoods had homes with minimal damage, but they had no water and wastewater services. In these scenarios residents were encouraged to live at home without services rather than seek housing in temporary shelters. Portable

toilets were placed on every block and portable showers were placed at community hubs while water and sewage systems were repaired. The recovery strategy was successful in bridging the gap between the earthquake event and the restoration of the infrastructure system, allowing individuals to stay in their homes with an acceptable level of service.

Over time however the portable toilets placed on the street became an unsatisfactory service. The region was subject to numerous large aftershocks resulting in frequent damage and setbacks in lifeline restoration. The portable toilets on the streets were undesirable to women and children due to a perceived or real safety concerns. Recognizing this, chemical toilets were used in subsequent outages (Johnson, 2013). The chemical toilets could be placed inside homes decreasing the distance to the service, and in terms of security, increased the quality of the service.

2.2 Local Disasters & Consequences

Earthquake case histories provide insight into lifeline system vulnerabilities, system interactions and consequences of failures. Because earthquakes are rare, general consequences have to be drawn from events across the globe. Small local disruptions caused by winter storms, large accidents, or even union strikes can provide insight into the consequences of failure specific to the region of study. Local events illuminate consequences that account for the local layout of systems, their interaction with other systems, and the local populations dependent on them. These small disturbances can be used to extrapolate consequences of a future earthquake. Appendix B, a Vulnerability Assessment of Bay Area Infrastructure, uses local cases to study Bay Area specific impacts of recent small failures and closures.

2.3 Quantifying the Probability of Damage

Damage occurs when a load is greater than resistance. Figure 8 demonstrates the relationship between loading and resistance in a graph. The loading produced by earthquakes are best represented by a wide distribution as their forces are uncertain. Resistance is also shown as a distribution; while structures are designed for a specific load, a number of variables result in stronger or weaker structures. For individual structures quantifying the probability of damage has become a relatively routine process. Both the resistance of the structure and the hazard loading are calculated either deterministically or probabilistically and can be compared to determine the likelihood of damage or failure. For single sites the hazard is generalized at a single point because the distance from known faults is static. The major difficulty with lifelines is that both the loading and resistance change continuously. Hazard forces are not static across regions. Each link of a lifeline system is above a unique soil profile and is a unique distance from a seismic source. Lifelines are spatially distributed infrastructure systems made up of many components with different levels of resistance. Lifeline resistance and hazard loadings are not static.

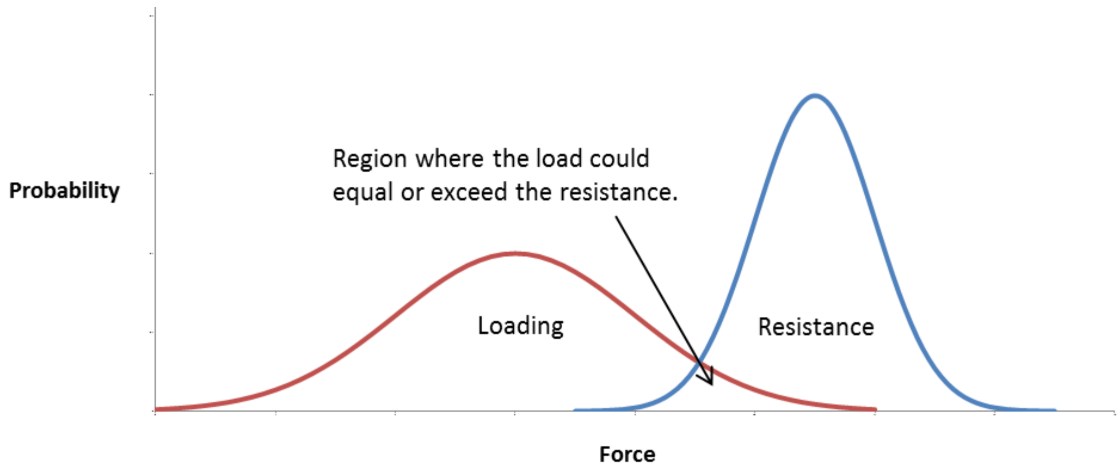


Figure 2.4: Load and Resistance Curves.

For analysis purposes systems are often segmented into links (e.g., pipelines, canals, roadways, power lines) and nodes (e.g., pump stations, interchanges, switching hubs, bridges) (see Figure 2.5) to organize the problem and assign single hazard levels and single resistance levels to discretized segments. Table 2.3 breaks down each lifeline into source nodes, nodes, anchor nodes, and links. Source nodes and anchor nodes describe key nodes either at the beginning or end of the system. Component is used to describe any piece of the system, either link or node. Depending on the vastness of the system and the resources and data available each component could be evaluated individually, each with a unique hazard and structural response.

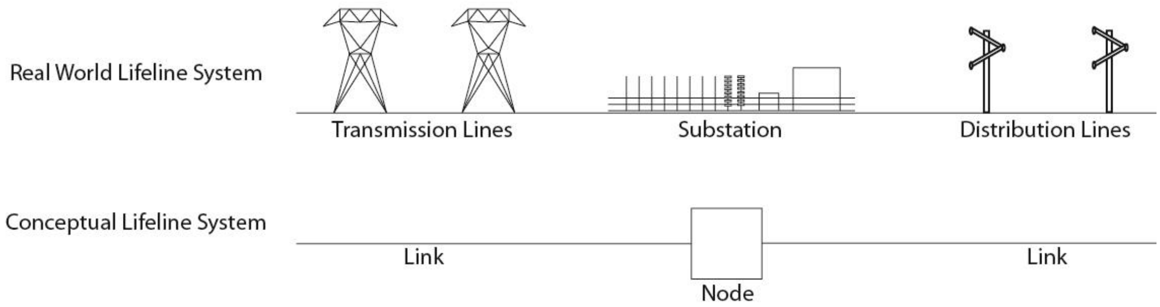


Figure 2.5: Conceptualizing and Analyzing Lifelines as Links and Nodes.

Table 2.3: Lifeline Components

Lifeline	Source Node	Transmission Links	Nodes	Distribution Links	Anchor Node
Transportation	Distributed Sources, Ports	Roads	Bridge	Roads	Distributed Sources, Ports
Electric	Power Plant	Power Line	Substation	Power Line	Distributed Sources
Gas/Fuel	Oil/Gas Fields, Refinery	Pipeline, Rail, Marine, Road	Pump Station, Terminal Station	Pipeline, Road	Distributed Sources
Water	Watershed, Reservoir	Pipeline	Pump Station, Treatment Facility	Pipeline	Distributed Sources
Waste Water	Distributed Sources	Pipeline	Pump Station	Pipeline	Treatment Facility
Cell Communications	Distributed Sources	-	Cell Towers	-	Distributed Sources
Internet Communications	Distributed Sources	Line	Root Server, Data Center	Line	Distributed Sources

Unfortunately, simply summing the damage states of each lifeline node and link together does not result in an accurate system assessment. A number of other probabilistic variables must be considered when multiple elements are responsible for a systems performance. System structure, interdependencies, cascading failure, collocation, damage states, spatial effects and correlation are critical for accurate system assessment. While each lifeline system has unique characteristics, generalities can be applied to all systems. As well as being significant variables for accurate analysis, effective mitigation strategies are often derivatives of these system characteristics. In

Chapter 5, the mitigation strategies discussed address one of these characteristics to improve the system reliability.

2.3.1 System Structure

Beyond the behavior of each node and link their organization can have a dramatic effect on the overall system performance. Lifelines are arranged in one of two simplified conceptual system structures, series or parallel. In a series system the failure of a single component results in entire system failure, while parallel systems have multiple components performing the same function allowing for operation as long as one of the parallel components is undamaged.

Most lifelines are series systems. If we visualize a lifeline as a chain, then the lifeline fails when any single "link" in the chain fails. This chain analogy is a functional definition of a series or non-redundant system. Figure 2.6 shows a functional series system when all nodes and links are performing (left), and a failed series system due to a single component failure (right). Examples of series systems include:

- A transportation corridor where the failure of any bridge or highway section will result in the closure of that corridor.
- A gas main where a rupture anywhere along its length results in disruption of gas delivery.
- A levee system where a single breach results in flooding on the protected side of the levee.
- An electricity grid that is down because a substation component has failed.

- A water canal where a fault has ruptured through the canal section thereby ceasing all flow downstream.

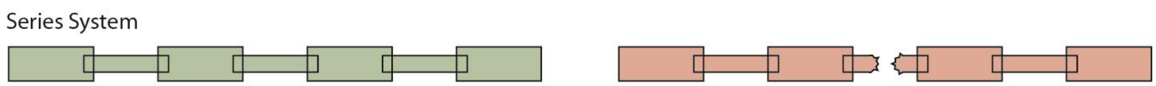


Figure 2.6: Series System Structure.

When multiple components or links have the same function, the system has a parallel design. This is also true when multiple modes provide the same service (Taylor & VanMarcke, 2002). To realize failure all components performing the same function must fail. Parallel systems decrease risk by increasing redundancy. Figure 2.7 shows a functional parallel system when all components are working (left), and a still functioning system with a single component failure (right). A key in having serviceable and functioning lifelines during or after a disaster is to build into the system redundancy, but as seen in the case histories ensuring redundancy is often difficult. In many cases lifelines are inherently series systems, or have series segments. Examples of parallel systems are:

- Two North/South highways with interchanges connecting between them.
- A North/South highway with a North/South passenger rail line.
- A water system with two separate source reservoirs that service the same area.
- A fuel refinery that can import or export fuel via pipeline, rail, truck, or boat.

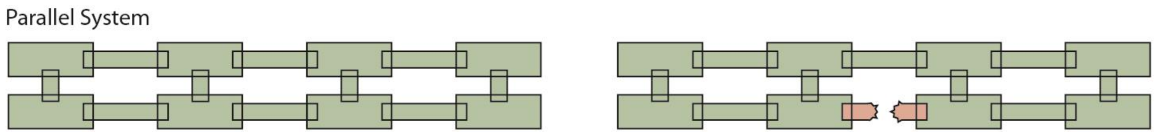


Figure 2.7: Parallel System Structure.

Systems that have both series and parallel components are called general systems (see Figure 2.8). General systems can be analytically modeled (e.g., Song and Der Kiureghian, 2003), but the difficulty in accurately mapping the complexity of general systems and more importantly the difficulty in properly accounting for the component correlation makes this an often untenable proposition. It's important to note that at larger scales most lifelines have the attributes of a general system. The complexity often increases when multiple modes of service exist. When there are multiple modes it is important to recognize geographically which portions are series (serviced by a single mode) and which are parallel (serviced by multiple modes). In the case of firefighting in San Francisco a multi-mode parallel system existed along the bay front, serviced by both AWSS and fire boats, but not at distances the fire boats could not pump water to.

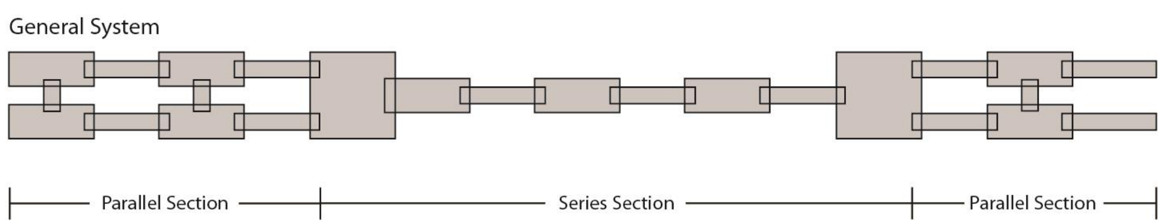


Figure 2.8: General System Structure.

When one piece of a parallel system is damaged a strain can be placed on the remaining link. The consequences of a component failure can be influenced by how near capacity the system is functioning on a day-to-day basis. Take for example a network of

interconnected roads that provide access from point A to point B, illustrated in Figure 2.9. This system can be considered a general system as there may be roads that are parallel and there may be interchanges that are in series. If this system is performing at or near capacity prior to some adverse loading situation, even a failure of a redundant component can result in system failure such as gridlock (Lewis, Mackin & Darken, 2011). However, if this system is running far below capacity, then there is inherent resilience in the system to absorb some component failure and continue to function. This relationship of system capacity to consequences adds a layer of complexity to systems analysis, making proper assessment of risk and reliability tricky.

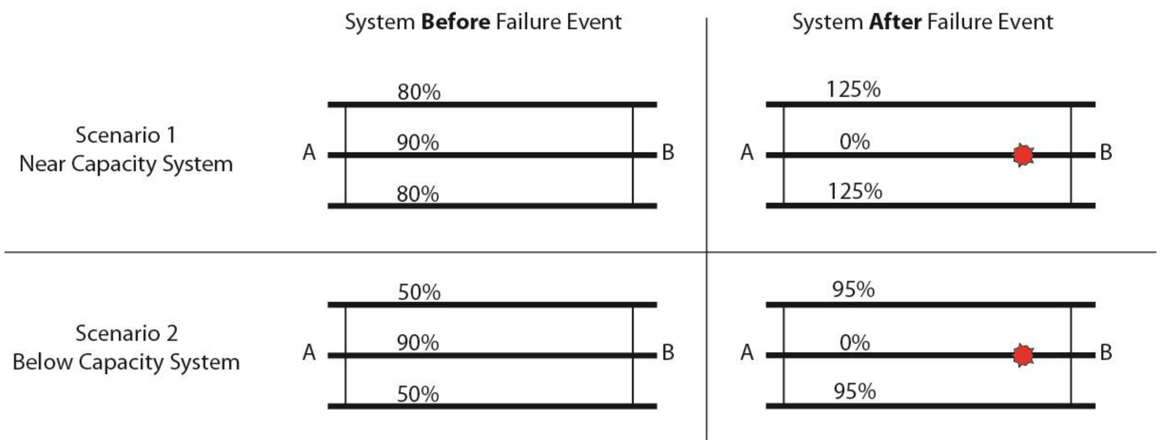


Figure 2.9: Capacity as an Element of Parallel System Performance.

The reliability of systems is greatly dependent upon the system organization. Analysis must acknowledging system structure. In non-redundant systems damaged components can result in service interruptions far from the point of failure (Taylor & VanMarcke, 2002). Designing new parallel systems to complement existing infrastructure can improve the performance of the overall system.

2.3.2 Interdependency, Cascading Failures, & Collocation

Interactions between lifelines can have negative cascading effects where the failure of one system causes the failure of another, a phenomena common in many urban earthquakes (Kameda, 2000). Lifeline interdependence is the reliance of one system on another. Interdependencies can hinder function, hinder repair, or physically damage the system. Cascading failures can happen both within a system and across systems and is used to describe the snowball effect of small initial failures. Lastly, collocation is when systems are located near to one another in space, resulting in simultaneous failure and often difficult coordination during repairs. Examples of these effects are highlighted below:

- A gasoline distribution system that is crimped by loss of electricity or transportation corridors.
- A water distribution system that is down because of loss of electricity.
- A communication system that is down due to severed land-lines and loss of electricity.
- A water system that is non-operational because a failed levee system has compromised the flow of fresh water.
- A bridge collapse that also severs communication, power, and water services that were attached to the bridge deck.

In Santa Cruz after the Loma Prieta earthquake a 35-hour power outage at a wastewater pumping station resulted in an 800,000 gallon raw sewage release (Schiff, 1990). The sewage release was not a result of facility earthquake damage, but rather the dependence on the failed electric service. The same interaction occurred in 2011 when a

cascading power grid failure caused by maintenance work at a substation outside Yuma, Arizona sparked a rapid fire 11-minute sequence of system failures where portions of California, Arizona, and Mexico lost power (Lee, 2012). In San Diego the electrical outage caused huge transportation delays and was responsible for more than two million gallons of sewage discharge (CBS, 2011).

In the above power outage cases it is irrelevant if the power failure was caused by maintenance error or a large hazard event. The magnitude of cascading failures has little to do with the hazard and more to do with the organization and design of the system. Cascading failures can be visualized with a single grain of sand continually dropped onto a sand pile until a "slide" occurs. This slide can be very small or it can bring down a majority of the pile. What causes a slide to be large or small has nothing to do with the single grain of sand, rather, "it has to do with the perpetually unstable organization of the critical state, which makes it always possible for the grain to trigger a [slide] of any size…as the sand pile evolves into a critical state, many grains rest just on the verge of tumbling. And these grains link up into 'fingers of instability' of all possible lengths," (Mauldin, 2012). The cascading effect starts with one small failure leading to another; very quickly a sand pile or lifeline system can be brought down. It is the interconnectedness of the underlying unstable structure that is the key to the massiveness of the final failure. While the magnitude and epicenter location of a future earthquake may be desirable predictions, the instability of the lifeline systems and their interconnection is what can lead to large failures.

> *"Catastrophic consequences arise when systems operate at or near their critical point a state whereby small, otherwise insignificant perturbations lead to*

unexpectedly large consequences. Normal accidents have three fundamental properties: (1) small failures can lead to large consequences, (2) nearly all large failures are the result of cascading small failures, and (3) failure propagation is enabled by interactions or the coupling of parts within the system. These attributes are associated with systems in a state of self-organized criticality (SOC). As SOC increases, the system nears a critical point where even the smallest perturbation can have disastrous results. Alarmingly many of our critical infrastructure sectors have reached self-organized criticality," (Lewis et al. 2011).

There are a few techniques that can limit the degree to which systems are self-organized-critically, where small failures cascade into large ones. Designing and operating systems below maximum capacity can provide for a surge in the system without failure. In 2010 the San Bruno Pipeline explosion demonstrated both cascading failure and surge capacity. An error in electrical maintenance work 50 miles away caused a pressure surge resulting in the failure and explosion of a weak portion of pipeline. The dependence of the gas system on electrical system and the inability of the pipeline to handle higher pressures are clear. The failure was caused by each of the three qualities of SOC. A few small failures at an electrical substation led to a large failure and consequence of the coupled natural gas line. Surprisingly, after the explosion natural gas was restored to all but a few blocks near the explosion despite a major natural gas pipeline being taken off line (NTSB, 2011). PG&E has three transmission lines that service the area downstream of the rupture. Had the overall system been at capacity prior to the explosion natural gas would have been interrupted to a large swath of the peninsula

and San Francisco. Because the system was running below capacity (partially due to the season) demand could be met by two other lines so no natural gas outage occurred, similar to the example in Figure 2.9. SOC qualities were responsible for the San Bruno incident, but the system design also lessened the number of households that experienced natural gas service interruptions.

Interdependency and cascading failures are often caused by the relationship between lifelines, and are independent of space. In the case of the Southern California power outage, the sewage failure occurred hundreds of miles from the electrical failure. Collocation is a geographic interaction between lifelines. Systems are often collocated due to the environments physical constraints. There are many corridors that bunch lifelines together; whether it is to pass a geographic feature (mountain or river) or due to limited public right of ways through an urban environment. When infrastructure systems are collocated a single failure can damage other systems unaffected by the hazard loading. In the San Bruno case, had the PG&E pipeline ruptured along another section when it runs adjacent to one of the other natural gas transmission pipelines, the collocation of the pipes would have resulted in failure of both pipes, and a natural gas outage for the San Francisco Peninsula. In addition to collocation causing damage across systems, it can slow restoration. Repair crews can be delayed by safety concerns, or by multiple crews working in the same area (Schiff, 1990). Gas leaks, wastewater leaks, can slow the restoration of other systems because of the hazardous conditions they create.

Recognizing interdependencies and collocation will make for more complete assessments of damage potential and restoration estimates. In 2008 as part of the ShakeOut exercise (a state wide earthquake drill and earthquake table-top exercise)

researchers brought together lifeline providers in the Southern California region to discuss the impacts of a M7.8 San Andreas earthquake scenario. Two panel discussions were held to determine the expected restoration of utility systems following the earthquake. In the first panel utilities only considered their expected restoration, due to earthquake damage only. At the second panel, utilities were given each other's expected restoration times and asked to re-evaluate their expected restoration now knowing how long they may be without services they depend on (Porter et al., 2011). Figure 2.10 illustrates the difference in expected restoration time of the electric system at each of the two panels. With knowledge of other expected system performance, and a desire to manage public expectations of system performance, the restoration of the power system was drastically impacted. In the revised estimate 10% of customers in Los Angeles, Riverside and San Bernardino Counties would not have service restored for over one year after the scenario earthquake. Including these qualities in an assessment not only offers an opportunity for infrastructure providers to communicate their expected performance to one another, but it also provides an opportunity to coordinate their mitigation work as well as their response to future failures.

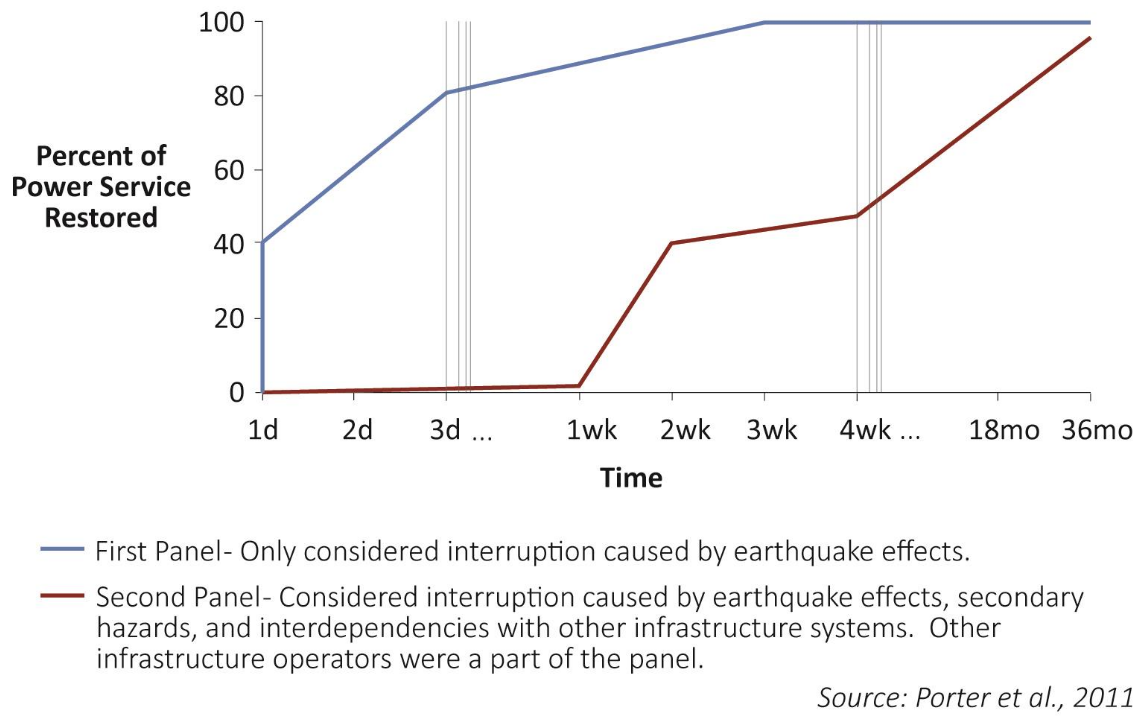


Figure 2.10 Southern California Edison Power Restoration Estimate in a M7.8 San Andreas Earthquake.

2.3.3 Hazards

In high seismic regions comprehensive seismic assessments are difficult. Systems pass over or near a number of faults each capable of a variety of rupture sequences. Earthquakes of equal magnitude on the same fault can produce different hazards across a region. Including the full suite of earthquakes and hazards in an assessment is a difficult task. A variety of methods exist to map and quantify hazards. Understanding what they show, and how they were developed is paramount in how they are used in a system assessment.

Seismic hazard maps are developed both deterministically and probabilistically. Deterministic maps are scenario maps for specific single events. Probabilistic hazard maps aggregate the hazard from a full suite of potential earthquakes, resulting in a single hazard level. Engineers use probabilistic hazard maps to assign a single value to assess the design level for buildings (single sites) accounting for all potential faults. These maps are less helpful when studying system performance of an actual event. Take for example a piece of infrastructure that crosses two faults in the Bay Area (see Figure 2.11). The probabilistic map (right) shows high hazards everywhere, when in a scenario event (left) only a portion of the region will have a high hazard while the other will have low hazard. When analyzing a system with probabilistic maps the performance in a single event is not studied and the analysis will result in greater damage than will actually occur in any one event.

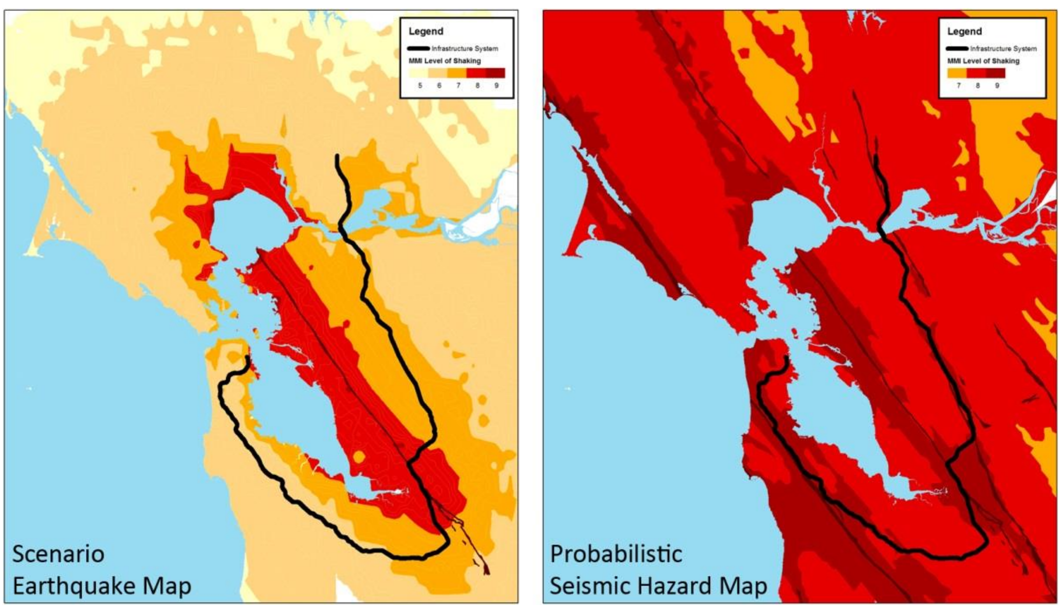


Figure 2.11: Using Scenario and Probabilistic Hazard Maps for Lifeline Assessments.

A deterministic approach allows system performance to be studied, but limits the number of scenarios analyzed; each scenario requires a new analysis. Only a single scenario or a chosen few can be studied resulting in an incomplete portfolio of earthquakes. For studies in the San Francisco Bay Area fifteen different fault would need to be considered. Each fault could be studied with multiple earthquake magnitudes and rupture characteristics. Figure 2.12 is a deeaggregation map produced by the Association of Bay Area Governments (ABAG). The map shows which faults contribute the greatest hazard potential for each location in the Bay Area. Discrete scenario events must be prioritized for lifeline studies, from highest to lowest hazard.

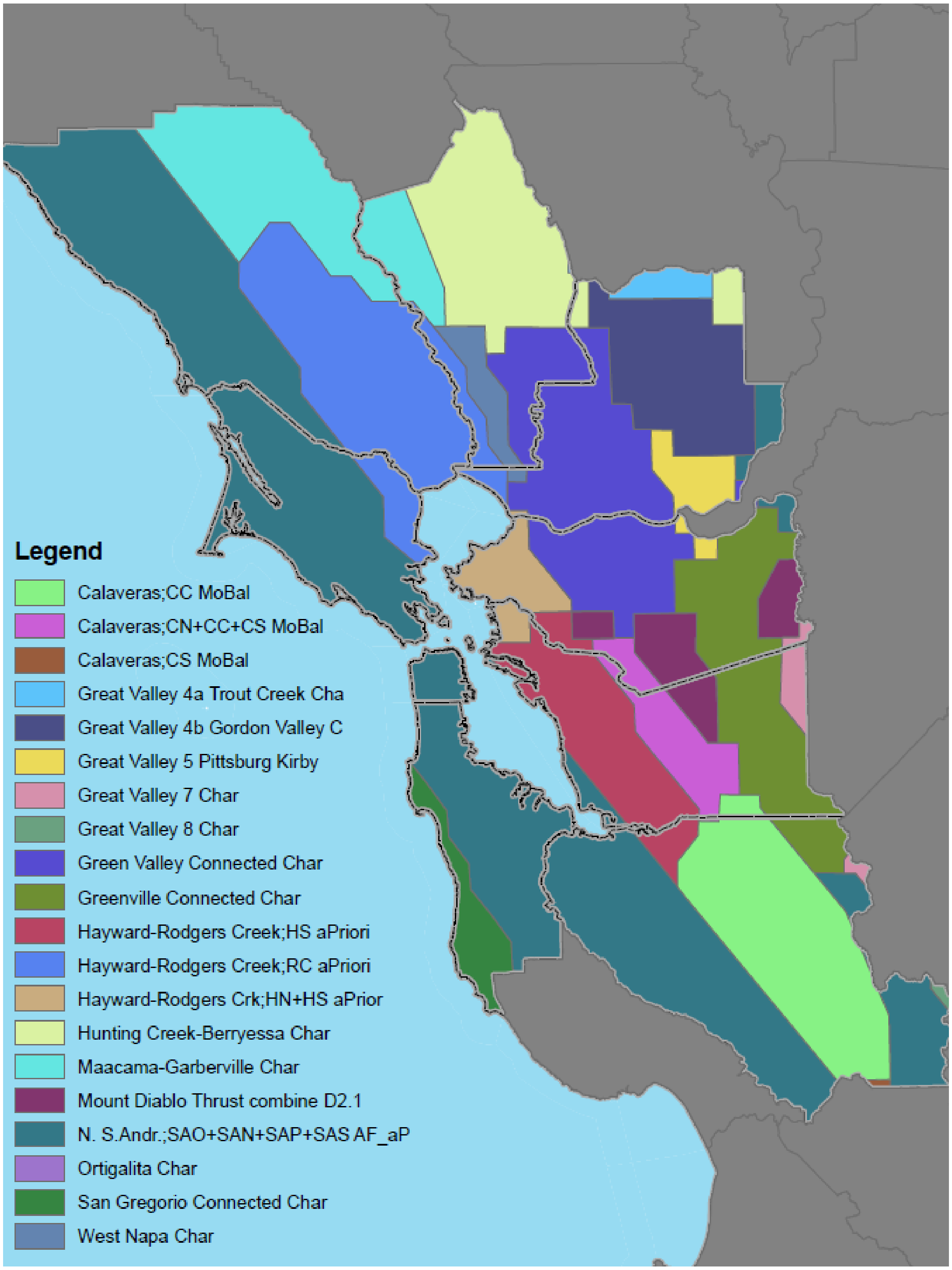


Figure 2.12: Deaggregation Map of the San Francisco Bay Area (ABAG, 2013a).

In addition to studying multiple events, there are a suite of hazard forces that must be considered; ground shaking, fault rupture, liquefaction, lateral spreading,

landslide/rockfall, tsunami/seich, and secondary hazards like fire following earthquake are each capable of damaging infrastructure systems and must be considered for a comprehensive seismic assessment.

- *Ground shaking* is measured in acceleration, often as a percentage of gravity. Shaking intensity does not attenuate uniformly outward from an earthquake epicenter due to a variety of terrains and soil conditions. Different soil properties amplify or dampen seismic waves as they propagate outward, and fault directivity, and topography all influence ground accelerations. Seismic waves can reflect off mountain ranges causing basin effects in regions like Mexico City and Los Angeles. In well mapped regions of the world these characteristic are already included in shaking hazard maps.
- *Fault rupture* is the hazard with the greatest level of certainty. The fault location is often known, and maximum probable rupture displacements for faults are known with some confidence. The relationship between earthquake magnitude, surface fault rupture length, and displacement have correlation coefficients of 0.84 to 0.95, providing decent predictions to be made on the fault rupture expected given the magnitude of the event (Wells & Coppersmith, 1994). Surface fault rupture can over multiple years, with the majority of the displacement occurring the day of the event, and the remainder occurring in the following year or two; this is the expected case for the Hayward fault in the Bay Area (Lienkaemper, Borchardt & Lisowski, 1991). The post-seismic slip can be difficult to manage as infrastructure may need to be continually re-straitened as the fault continually creeps. This is of special concern for systems like rail that

cross large faults that could require continual re-straightening of tracks for years after an earthquake.

- *Ground failure, liquefaction, lateral spreading, landslide, and rockfalls,* have also been mapped with varying levels of uncertainty by the USGS. Liquefaction is the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore pressure and decreased effective stress. Liquefaction can result in ground settlement, loss of baring capacity (often impacting the performance of foundations), and lateral spreading which occurs when liquefaction occurs on a slope or near a free face. Liquefaction is common in areas with high water tables, and certain sandy soils (often near existing or historic water features). Similarly, earthquake induced landslides and rockfalls occur when the stability of slopes is disturbed by ground shaking. Severe liquefaction or landslides can cause significant damage to lifelines, but even embankment settlement of a few inches can cause failures and closures of road and rail lines. When lifelines cross over hundreds of miles of environment, the soil profiles and topography are dynamic variables that are important in accurately representing the seismic hazard (Kameda, 2000; Song, 2009). Soil and structure interaction has had a drastic effect on performance. In the 1989 Loma Prieta earthquake 100 of 150 total pipeline breaks were in the Marina District, a direct result of the local soil failures (Schiff, 1990). Including ground failure in a lifeline assessment is necessary as so many of system links are vulnerable to damage due to soil failures, even more so than shaking.

- *Tsunamis and seiches* can be caused by off shore subduction earthquakes, by above or under water landslides that displace large amounts of water, or volcanic eruptions. Both the flooding caused by tsunamis and the water flow are responsible for damage. In large events they can cause complete damage across a region, but even small tsunami heights can cause damage to key infrastructure facilities located near the water (ports, wastewater treatment plants, public right of ways along waterfronts, etc.) due to both inundation as well as high currents as water flows in and out of bays or marinas.
- *Secondary hazards* following earthquakes are common and have been responsible for more damage than the shaking. The 1906 San Francisco earthquake shook the city, but the resulting fire devastated San Francisco, "The two largest peace-time urban conflagrations in history have been fires following earthquakes – 1906 San Francisco and 1923 Tokyo, the latter event's fires causing the great majority of the 140,00 fatalities," (Scawthorn, 2011). Fires following earthquakes are common and visible directly after an event, but public health is another issue that can occur with damaged wastewater systems.

Understanding how earthquake hazards change with space is an important quality to consider. Because systems span large distances each component will experience different forces. Quantifying and mapping the hazard across a system will influence the expected performance of each component and will help highlight which components of existing systems are most susceptible to severe hazards.

2.3.4 Correlation

Correlation coefficients are used to account for influence between components. When analysis is performed on systems with more than one component correlation must be included for accurate assessment. Ang and Tang describe the correlation coefficient (p) as “a statistical measure of the degree of linear interrelationship between two random variables,” (Ang & Tang, 2007). The performance of a single component in the system drastically alters the likelihood of survival or failure of a neighboring system component.

Correlation values range from -1.0 to 1.0. Positive values correspond to components likely to respond similarly (i.e. if one is damaged, the other is likely damaged), negative values mean components are likely to respond differently (i.e. if one is damaged, the other is likely undamaged). Large correlations, values near -1.0 and 1.0, dramatically influence system performance. Values near zero are weakly correlated and don’t impact system performance; component performances are independent.

The following common textbook example demonstrates this. Two widgets fabricated at the same plant on the same day and installed identically are likely to respond similarly when subject to similar loadings, and would have a correlation value close to 1.0. The performance of one widget will influence the predicted performance of the second.

For lifelines each component in theory will be uniquely correlated to all other nodes in the system based on its unique characteristics. Most lifelines are an amalgamation of varying construction types, ages, materials, and design codes all of which influence the predicted resistance of system components. The spatial location and

soil type will influence the loading relationship between system components and is also correlated.

2.3.5 Varying damage states

In many discussions of probability the focus is on the probability of failure. This is an insufficient analysis when there are multiple damage states. “Generally, components can have different classifications depending on their use and how they are defined. There are single state components, e.g. always working, two state components, e.g. failed or safe, and multi-state components, e.g. lightly damaged, moderately damaged heavily damaged, collapsed,” (Hollenback, 2014). Components are often defined as either brittle or ductile to describe their variety of potential states. Brittle systems are two state systems that are either failed or working, while ductile systems can have any range of function. With each increase in possible states, the outage time gets more difficult to predict as there are more potential outcomes increasing the problem complexity. Because of this, brittle systems are generally simpler to analyze.

A brittle system either provides zero service or 100 percent service. Quantifying the outage is easy to measure. Electrical systems are brittle systems; they either provide power or do not. Transportation systems are at the ductile end of the scale. A variety of road damage states result in various levels of service (i.e. one lane open, restrictive service, heavy traffic). Figure 2.13 shows the difference between brittle and ductile performance. Brittle components (right) either resist the load or fail, there are no in-between damage states. Ductile components (left) have a range of damage prior to

failure. Distributions are used to describe the range of possible loadings and resistances. The wider the base is influences the greater range of possible values. Earthquakes and other natural hazards are tricky because loading distributions are often lognormal (Petersen, 2007) with long tails for high loading levels. With some probability of very large loading forces it can be difficult to determine an ideal loading to design resistance to.

Figure 2.13: Brittle and Ductile Component Performance.

In addition to analyzing each systems varying damage state, understanding their collective impact on a household or business is much trickier than understanding the impact of structural or non-structural damage. If a facility is reliant on all lifelines its functionality may change when only a fraction of the systems are restored. There are a number of outage combinations each with a different impact. Facility damage often causes complete interruption (easy to quantify), while lifeline outages often result in a range of losses (difficult to quantify). Depending on the economic sector, or the internal preparedness and resilience of an organization or household will determine how critical lifeline interruptions are.

Accurate assessment requires the measurement and inclusion of probabilistic variables and system characteristic; however, as described these methods can be difficult to quantify and increase the time required for analysis. Simply ignoring the variables will result in an incomplete inaccurate assessment but including them as theory suggests is currently an unrealistic goal. Section 3.4 will present methods to include these variables in unique ways to compliment the simplified methodology.

2.4 Consequences of Damage

Quantifying the probability of damage and developing restoration curves/maps is only half of the risk equation, understanding the consequence of outage is the other half. Disasters consequences are measured in losses. Casualties, property damage, and business interruption are all used to measure loss. A number of sociological impacts are also experienced but are difficult to quantify. While they should be considered at least qualitatively in the decision making process, this study will not focus on the sociological impacts. This research will focus solely on direct and indirect economic losses.

Direct and indirect losses occur due to both site damage and lifeline damage. Direct losses include damage to physical objects, while indirect losses are costs associated with interruption. In the case of business, direct losses primarily occur from damage caused to the facility and the contents of the facility during the event. Indirect losses could be measured by lost revenue while the business is closed for reconstruction. This same business could incur indirect losses if lifelines it relies on to function are unavailable. Both direct and indirect lifeline losses are discussed below.

Direct losses are the easiest to quantify. They consist of the finances required to repair physical damage. This includes demolition, waste disposal, and construction costs, all of which come with receipts. For lifelines, these costs directly impact the utility or municipality. In many cases lifeline vulnerability studies undertaken by the utility provider are heavily concerned with direct losses because these are the losses that they will incur in a disaster. When this is the case, a component by component assessment is an acceptable method because the system performance is less important. The provider is attempting to limit physical damage at each component of the system. By prioritizing mitigation with this methodology the system performance is simultaneously improving (as any mitigation work is beneficial), however the mitigation prioritization does not consider system performance nor indirect losses. With a wider lens for impacts, direct lifeline losses can be a fraction of the total losses.

Indirect losses are driven greatly by loss of lifeline service to homes and businesses. Examples of indirect losses are business closure, increased travel time, and disruptions in consumer habits. Businesses with negligible site damage can be closed when without lifelines. Lifeline outages caused by damage hundreds of miles away can close businesses, just as a closed business in one city can impact supply chains globally. Businesses have increasingly moved to a just in time production strategy where single disruptions and a lack of secondary options can halt production lines inside and outside of the disaster zone. Very few businesses are self-sufficient, and require a host of other businesses from coffee shops to software companies to fully function. "One enlightened company executive recently summarized the situation quite poignantly: "In short, companies have started to realize that they participate in a greater ecosystem –and that

their IT systems are only as resilient as the firms that they rely on to stay in business,"" (Rose, Liao & Oladosu, 2007). Losses can be amplified by the indirect economic impacts which, "significantly increase the size of the damage as it ripples throughout the economy beyond those businesses whose electricity service is directly curtailed," (Rose et al. 2007). For businesses reliant on a lifeline the magnitude of the indirect losses is often a function of outage length.

The relationship between outage time and losses was well documented following the 1994 Northridge earthquake by Dahlhamer, Webb, and Tierney. A large sample of businesses were surveyed to determine the losses due to telephone, electric and water outages. Figure 2.14 clearly shows relationships you might expect ranging from linear to exponential.

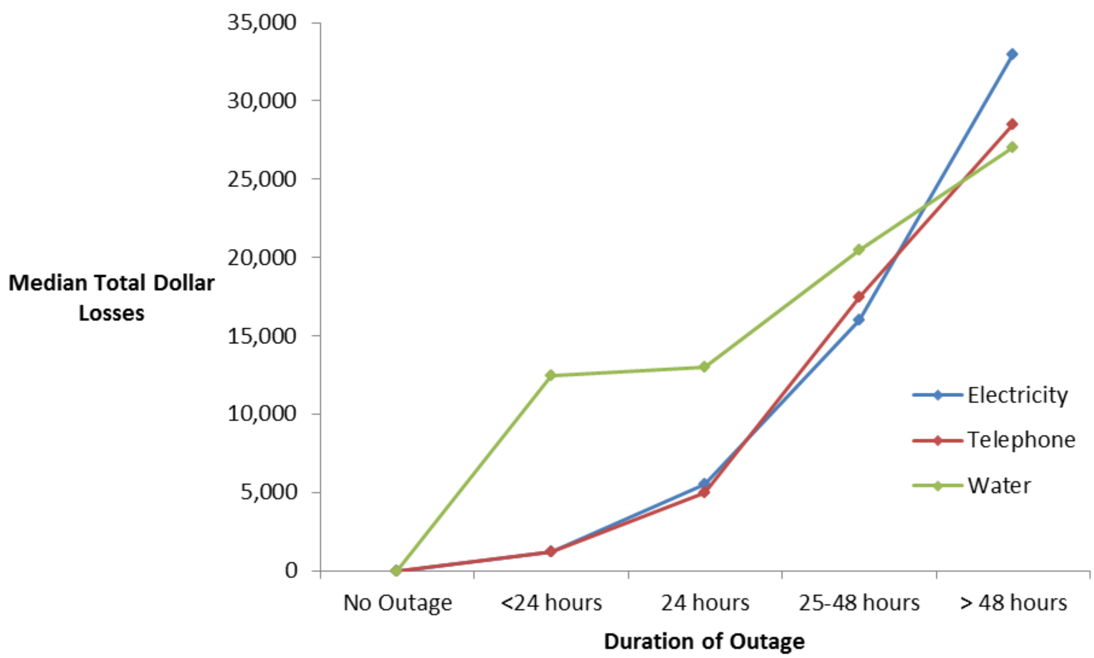


Figure 2.14: Impact of Lifeline Outage Lengths on Individual Businesses Following the Northridge Earthquake (Dahlhamer et al. 1999).

A prior study by Tierney surveyed the cause of business closures following the Northridge earthquake. Along with site damage, electric, transportation, and phone outages were the top four sources of business closure, while water and waste water were much lower on the list (see Table 2.4) this could be due to the fact that water and wastewater were only lost on average for two and three days respectively. As seen in Figure 2.14 (Dahlhamer, 1999) losses due to water take effect after 24 hours. A similar relationship might exist for wastewater.

Table 2.4: Reasons for Business Closure, Northridge Earthquake

Reason for Business Closure	Percent
Needed to Clean Up Damage	65.20%
Loss of Electricity	58.7
Employees Unable to Get to Work	56.4
Loss of Telephone	49.8
Damage to Owner or Manager's Home	44.4
Few or No Customers	39.9
Building Needed Structural Assessment	31.5
Could Not Deliver Products or Services	24
Loss of Machinery or Office Equipment	23.7
Building Needed Repair	23.4
Loss of Inventory or Stock	21.9
Loss of Water	18.2
Could Not Get Supplies or Materials	14.9
Building Declared Unsafe	10.1
Could Not Afford to Pay Employees	9.5
Loss of Natural Gas	8.7
Loss of Sewer or Waste Water	5.3
Other	15.8

*Number of Closed Businesses Surveyed (617)

(Tierney, 1995)

The same study was completed following 1993 floods in Des Moines, see Table 2.5. In that event both water and wastewater outages were longer (median of 12 days) and represented two of the top three reasons for closure. Wastewater and water outages

likely would have been a larger cause of business closure in Northridge had the outages lasted beyond the initial one or two day resilience threshold of most businesses.

Table 2.5: Reasons for Business Closure, Des Moines Floods

Reason for Business Closure	Percent
Loss of Water	63.60%
Loss of Electricity	41.7
Loss of Sewer or waste water service	34.8
Few or no customers	34.4
Loss of telephone service	28.3
Employees unable to get to work	26.3
Could not deliver products/services	*25.7*
Evacuated due to threat of flooding	21.4
Building was flooded	19.9
Could not get supplies or materials	16.3
Loss of machinery/office equipment	15.4
Loss of Inventory	11.9
Building was declared	6.9
Damage to owner or manager's home	6.9
Loss of natural gas	6.9
Could not afford to pay employees	6.7
Other	21.6

*Number of Closed Businesses Surveyed (448)

(Tierney, 1995)

These studies represent a relationship two decades old. The relationship between lifelines and users has changed over the past two decades, but there have been no recent studies as comprehensive as those completed 20 years ago. When considering earthquakes in the 21st century, some lifelines may be more or less important. Communications and electricity may be more important with more work being stored in devices that require electricity or connection to data servers across the globe. While businesses and the public may be more sensitive to electricity or communication lifelines they may be less sensitive to transportation interruptions as a result of people telecommuting or a trend in people living closer to work.

The consequences of lifeline outage need to be quantified to measure risk. Knowing only that damage will occur does not provide decision makers with all the required information. Smaller businesses and institutions may be able to quickly quantify probable losses while larger businesses with multiple processes may require more intricate analysis. From a regional perspective development of refined economic loss models are popular for determining direct losses, but back of the napkin calculations often are in the same order of magnitude. For the electric sector, disruptions in the United States have been quantified by using a ratio of \$1.50 to \$7.50/kWh (Rose et al. 2007). Using these estimates the 1996 blackouts in California "are estimated to have cost more than \$1 billion in direct losses. A more recent estimate of outage costs to business is as high as \$50/kWh for some sectors. An application of such estimates placed the cost of the 2003 northeast blackout at more than \$6 billion," (Rose et al. 2007). The losses of outage will vary greatly between the lifeline and the business sector. Some sectors may represent losses \$1.00 while others are 50 times greater. Depending on the audience of an assessment the losses can be specific to a business with a detailed list of consequences, or broad, highlighting regional economic impacts. Broad generalizations can be made for regional economic impacts to influence government, however to influence individual businesses a more detailed list of consequences and losses will be beneficial.

3 METHODOLOGY FOR SIMPLIFIED INFRASTRUCTURE ASSESSMENT

"Questions are often raised from engineers of lifeline sectors that a rational basis should be provided by which the post-earthquake performance of lifelines can be evaluated in a way that societal consensus or acceptance is realized. To do this, it is indispensable to incorporate evaluation of lifeline performance in an appropriate manner from the users' side," –Hiroyuki Kameda.

By considering the consequences of lifeline failure, system assessments can be reduced to focus the analysis on catastrophic risk. The resulting assessment is abbreviated, but provides a feasible methodology to explore risks that are currently unstudied. The limitations of existing methodologies are bulleted below followed by an outline of the proposed methodology. Each section of the chapter then explains every step of the methodology in detail, highlighting the issues resolved by the assessment.

Despite societal reliance on lifelines many users are unaware of the risk. Without an understanding of the existing risk there is no baseline for predicting the benefits of mitigation, nor guidance to take calculated action. Lifeline systems are largely unstudied, and when they are, they are often assessed from the perspective of the lifeline operator. The following are general barriers that often prevent actionable lifeline risk assessments.

1) Many systems are considered too complex and disperse to assess, so it simply has never been attempted.
2) There is no data to complete an assessment. Most utilities know geographically where their systems are, but very few have attribute information for each component that describes the material, age, condition, soil properties, etc of system components.

3) When data does exist the assessment is often completed by the utility provider who is the stakeholder. When consequences are examined they are often only measured by direct losses to individual components, rarely measuring consequences to the system and to users.

4) When assessments are completed they are often not available/communicated to the customers to set an end user expectation.

Two main issues can be distilled from the lists of barriers. First, it is often infeasible to generate a complete system vulnerability assessment, especially for those without direct access to system data. Second, consequences for the users are often ignored. The typical assessment often focuses on the utilities perspective, studying vulnerability first and consequence second. By studying vulnerability first, many system analyses are thought infeasible. Secondly, by focusing on the consequence to utilities the vulnerability assessment may be structured to measure direct losses only, limiting its utility as a resource to other stakeholders. In the simplified methodology presented here the process is flipped. Consequences are measured first and used to simplify the lifeline analysis by ignoring negligible outcomes. Stakeholders approach the problem, considering what outages result in catastrophic losses, and then an abbreviated assessment is developed based on the bounds generated by stakeholder input. The proposed methodology herein offers a simplified system assessment that addresses the barriers above. The simplified model does not provide a complete assessment of lifeline performance, but does provide insight into the catastrophic system risk. There are four steps in the simplified system assessment:

(1) Determine the stakeholder for the study. It could be a region, a single city, or even an individual institution.

(2) The stakeholder then sets acceptable level of service bounds for each lifeline to determine what outage would cause *severe* losses.

(3) Reduce the system to elements that govern restoration. Also, set a geographic boundary of analysis and a hierarchy to bound relevant system components.

(4) Explore and apply system probability variables to the simplified system.

The proposed methodology does not consider the probability of small disturbances and focuses analysis on outages that will cause catastrophic losses for the stakeholder. The methodology accomplishes three important things. First, it allows systems to be simplified to fewer components, making an assessment more feasible. Second, it prioritizes the study of consequences rather than just the probability of failure; and lastly, it focuses study on catastrophic risk, addressing resilience. Losses are inevitable in disasters, but to achieve resilience one must be concerned with preventing catastrophic losses. When attempting to make a family, business, or region resilient, efforts should be placed in preventing losses that are too great to recover from. The next four sections go into detail the four steps of the simplified methodology.

3.1 Identify Stakeholders

The stakeholder(s) influence the degree to which the system can be simplified. Currently, the majority of assessments are completed by the lifeline operator. They have access to their own systems data and have the greatest understanding of how their system operates. Through the lens of the utility consequences will largely be measured by direct

losses (damage to the system). In some cases a complete study may also include lost sales during interruption. Lost sales begin to address indirect losses but fail to measure the greater economic losses associated with business interruption. To illustrate the gap in indirect losses consider a simple example. A child's lemonade stand sells 1 gallon of lemonade on a regular day, for a total profit of $10.00. Because of a water outage, the lemonade stand is forced to close. In this scenario the lemonade stand loses $10.00, while the water provider loses one gallon of water sales, roughly $0.004. Simply put, if a businesses closed because of a water outage their losses can be significantly greater than their water bill. When a user (business, city, or region) is the stakeholder, indirect losses become much greater. Including appropriate stakeholders can expand which consequences are considered and can help bound and simplify the analysis.

Identifying users as the stakeholder focuses on indirect losses caused by outage. But users are a broad stakeholder group, making consequences difficult to measure. There will be times when the stakeholder is predefined by the client, but when there is the freedom to narrow there are unique relationships that may help focus. Any stakeholder can be used within the methodology, but certain groups may be more action-oriented to results. Some stakeholders are impacted more by infrastructure outages and may be more likely to act when provided information.

At a first pass, lifeline outages may be expected to be more critical the closer a facility is to a hazard; however, lifeline outages have a greater potential of being the governing reason for closure if a facility is removed from severe damage. Properties nearer high intensity shaking or liquefaction zones have a higher probability of experiencing facility failures in which case lifelines are potentially not an immediate need

and will be repaired before the facility will require them. Recovery is dependent on lifelines when structures do not suffer significant structural and nonstructural damage. For these facilities recovery is dependent on how quickly lifelines can regain their services.

Stakeholders who have previously retrofit or designed to a higher standard have a similar circumstance. Lifeline losses are most critical to those who have mitigated their facility via retrofit or other methods. Their structures are likely to experience minimal damage in a seismic event, which means lifeline failures will govern the functionality. This group of individuals may help to both frame the problem and may be eager to discuss possible lifeline mitigation and preparedness solutions.

Generally speaking lifeline systems are more fragile than buildings (Figure 3.1). The fragility curves below are from a Japanese study in 2005. JMA is a similar scale to MMI; the relationship between JMA and MMI are shown to the right of the fragility curve. The numbers are not of primary interest here. What is important is that building fragility curves are to the right of infrastructure systems. If the fragility curve of a building is to the right of the infrastructure system relied on, then lifelines are more likely govern recovery. This is a potentially powerful relationship when attempting to engage stakeholders. Those that have retrofit in the past have two unique qualities, (1) in the past they recognized and mitigated risk, (2) lifelines govern their recovery.

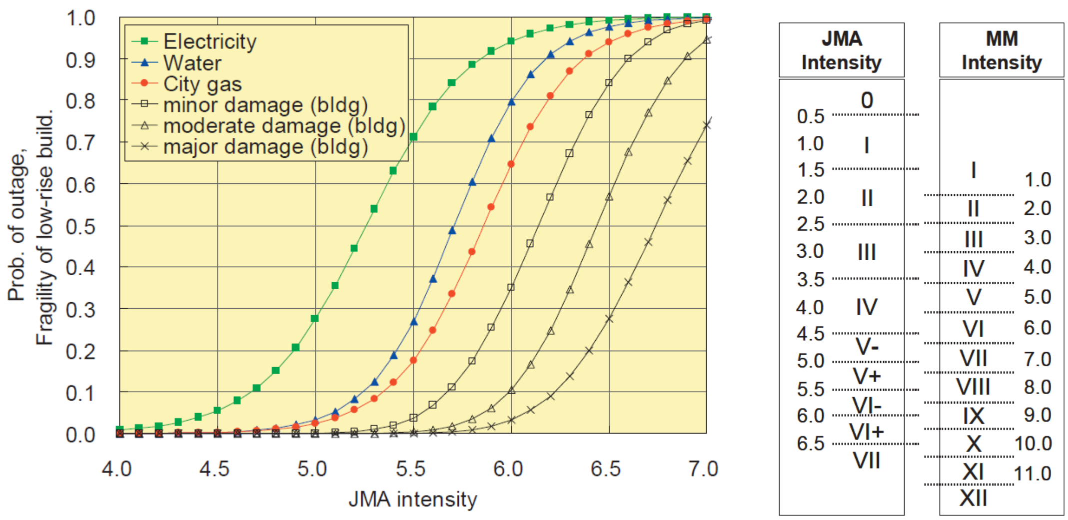


Figure 3.1: Relative Fragility Between Lifelines and Low-rise Buildings (Nojima & Sugito, 2005).

Defining the stakeholders for the study is an important first step. Differences between infrastructure operators and users can lead to drastically different assessment methodologies. Selecting users as the stakeholder focuses consequences on indirect losses. When appropriate, the wide spectrum of users can be narrowed to those that have a low risk of facility failure, because they are more likely to have lifelines govern their restoration, making them a unique stakeholder to consider. The next section explores in detail the relationship between users and lifelines.

3.2 Outage Time and Acceptance Curves

The relationship between users and infrastructure systems provides insight into consequences, and is the driver of the proposed methodology. This section introduces acceptance curves and resilience properties as a means to measure the consequence of

infrastructure outage. Stakeholder processes are then explored to understand the relationships between infrastructure systems. This step aims to accurately measure user consequences to outages. In short, users communicate which lifelines are most important and the relationships between them, to determine which outages are acceptable. This sets the stage to simplify the system in Section 3.3, and properly organize probabilistic variables in Section 3.4.

First is the concept of acceptance curves. Acceptance curves are a user's acceptance given an outage, most simply measured against time. What is an acceptable outage can be a blurred and difficult question to answer because no losses are good. As outages progress the losses only get larger. Ideally a critical point can be discerned, where an outage results in permanent irrecoverable losses. The critical point is c as described in chapter 1, EQ 1.3. For a business the critical point might be when projects are not just suspended but are lost. For a region it may be when residents and businesses decide to permanently relocate elsewhere. If restoration of lifelines occurs before the critical point is reached there are no continued losses as a result. Figure 3.2 illustrates scenarios where restoration of lifelines occurs after and before the critical point. When restoration occurs after the critical point is reached (top) there are permanent irrecoverable losses. When restoration occurs before the critical point is reached (bottom) there are no permanent losses. The lines are shown as linear functions for simplicity. An actual stakeholder will likely have unique, nonlinear relationships between outage times and losses. Understanding where to set the critical threshold for stakeholders then allows for a restoration goal to be set.

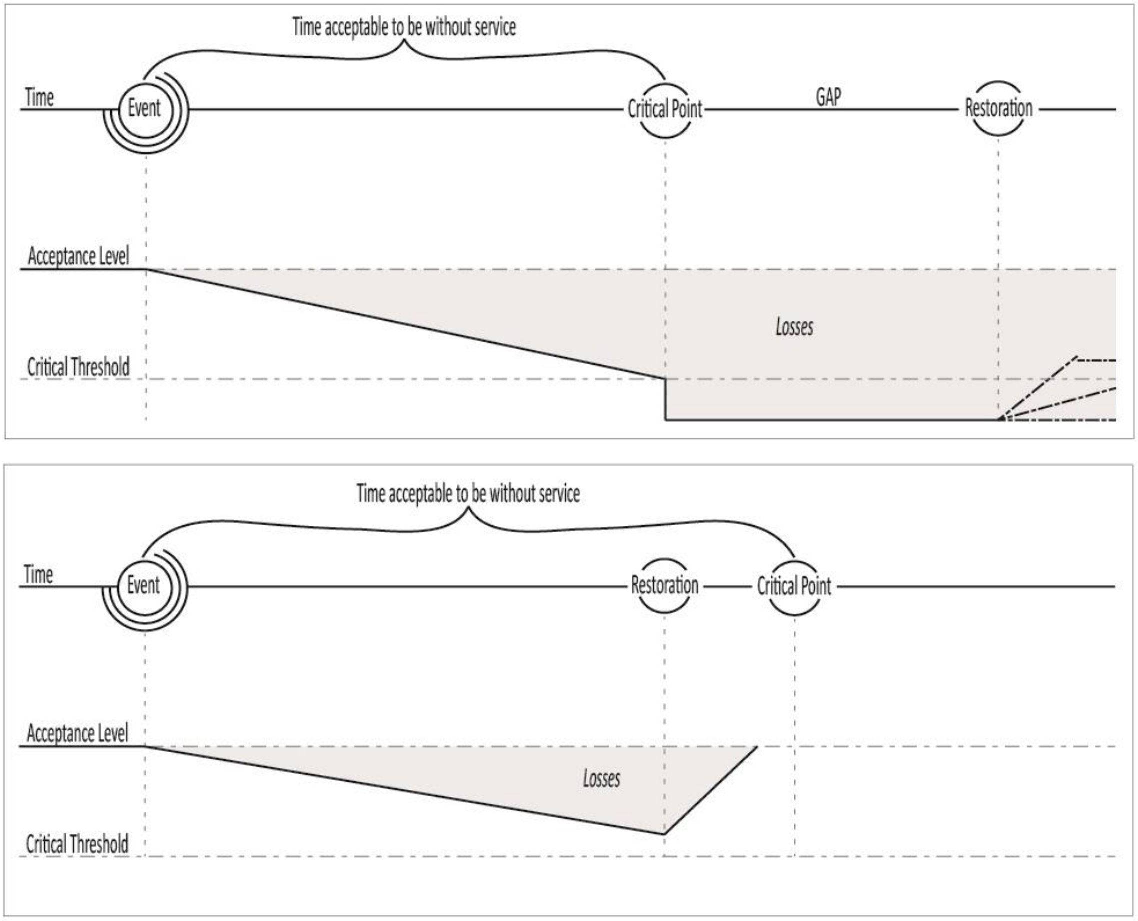


Figure 3.2: Losses with Restoration After and Before the Critical Point is reached.

The ability of an organization or community to absorb initial losses and return to pre-disaster position is often characterized as resilience. The resilience triangle, Figure 3.3, illustrates all types of loses (building loss, lifeline outage, etc.). The smaller the initial dip the more robust the organization is. The smaller the length, the more repairable the damage is. A resilient community/organization will minimize their triangle and return or surpass the baseline trend. Considering only lifelines, resilience can be achieved by either minimizing the duration of lifeline outage, or by preparing to cope for an outage without significant social and economic losses. "One of the major factors in

evaluating the economic impacts of utility lifeline outages is resilience, or the ability of an individual, organization (e.g., business), or institution (e.g., market) to cushion itself against maximum losses," (Rose et al. 2007). The further an organization can push out their critical point the more resilient they are, and the easier the lifeline assessment becomes.

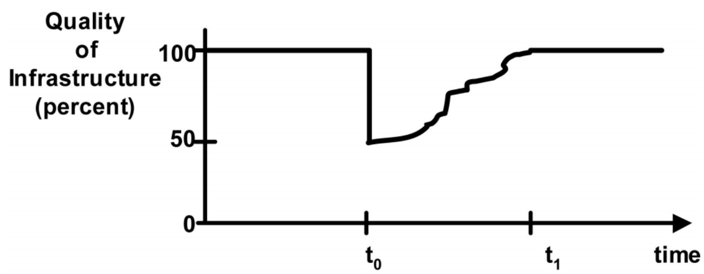


Figure 3.3: Resilience Triangle (Bruneau et al. 2003).

To prevent catastrophic losses restoration must occur before the critical point. Acceptance curves are used to help determine the design level and recovery strategies necessary to prevent catastrophic economic and social losses. "People can stand lifeline disruptions for some period immediately following the earthquake. But as a reduced level of supply is sustained, their demand will increase and the individual users' acceptance curve decreases with time," (Kameda, 2000). Following the Kobe earthquake, the Kobe Municipal Water Supply surveyed samples of the population to gauge the difficulties faced without water. Drinking water was trucked in, but sanitation was a massive problem. Some portable facilities were available, but there were insufficient resources to go around (Horwich, 2000). Those who were without water service for longer than four weeks had excessive difficulties due to the water outages. Researchers tracked customer calls over the four week period - emotions changed from inquiry, to complaint, to anger,

and then desperation (Kameda, 2000). In order to match the acceptance curves of their customers the Kobe Municipal Water Supply designed their system to provide water service to all customers within four weeks following a future earthquake.

Measuring the outage time alone can be an incomplete metric that only partly considers the consequence of failures. Studying other acceptance scales provides a more complete understanding of consequence. As noted in Section 2.1.5 Christchurch citizens remained in undamaged homes for months despite water and wastewater outages. They were able to minimize losses and allow for homes to remain habitable because temporary water and wastewater services were distributed at a high enough quality and quantity within a reasonable distance. Lifeline service following a disaster should be measured on four interdependent scales (Kameda, 2000):

(1) Outage Time

(2) Quantity of Lifeline Service

(3) Quality of Lifeline Service

(4) Distance to Service.

These four scales determine the severity of lifeline loss and are helpful in determining the design level of lifeline systems and the recovery strategies necessary to prevent catastrophic losses. The relationship between the four scales can simplify analysis hierarchically as well as provide cities with a metric to improve community capacity for coping with outages. In Christchurch the portable water and wastewater services were successful in bridging the gap between the first earthquake event and the restoration of the lifeline system, allowing individuals to stay in their homes with acceptable level of service across all four scales. After the second large earthquake in

Christchurch however, chemical toilets were used in many neighborhoods instead of outdoor portable toilets. This change can be well modeled by acceptance curves. The distance to service and the quality of service (mostly safety) were improved upon. These measures drastically increased the time residents could live without typical water and waste water services. In large events where the main system will require weeks or months to repair, there should be methods in place to provide an acceptable quantity and quality of service within a reasonable distance. The relationship between time, quantity, quality, and space are important to consider when quantifying consequence and designing recovery strategies.

System assessments can be studied individually with acceptance curves but when measuring consequences it is beneficial to also consider lifelines together. When developing an understanding of what causes failure the stakeholder should explain what processes are necessary. For example, having a way for employees to commute to work is important for most businesses to function. In the case of personal vehicle transportation this process is directly reliant on both roadways and fuel. When studying this process it is better to consider the vulnerability of these systems together. When regions or institutions are reliant on multiple lifelines and a single lifeline outage can cause failure, all systems must perform for losses to be avoided. In the case of a business reliant on multiple lifelines the probability of failure (business closure) is the union of each lifeline outage.

$$PF = LL_1 \cup LL_2 \cup LL_3 \qquad \textbf{EQ 3.1}$$

In 1991 the Japan Society of Civil Engineers outlined issues that the lifeline community needed to address. The committee noted that balanced preparedness among

different systems and information sharing between different lifelines would help prevent losses (Kameda, 2000). Beyond the reliance of lifelines on one another, organizations with failures caused by multiple lifelines require mitigation to be balanced across all systems. In the case above if roads are not impacted by an event but fuel is, commuting may not be possible. In many disasters electricity is restored well ahead of other systems. Had Christchurch not distributed water and wastewater facilities it may not have mattered if electricity was restored because people may have had to leave without the other services.

Understanding these relationships is important for properly measuring consequence as well as for understanding unique mitigation options. Section 3.4.4 discusses these issues further and expands on the commuting example.

3.3 Simplifying the System

Lifeline systems can be reduced to components that govern catastrophic disruptions by using the acceptance curves developed in Section 3.2. By reducing the system, previously large complex lifelines may be more easily analyzed. The reduction of the system must be completed in a thoughtful manner. Removing components that strongly influence system performance will result in an inaccurate analysis, but a lack of thinning can result in an unnecessarily large or infeasible analysis. Acceptance curves, repair times, hierarchy, and geographic scope are all used to reduce systems. The subsequent analysis of the reduced system will provide a catastrophic risk profile that highlights system components that could result in catastrophic consequences for the stakeholder(s).

The system is bounded first using geographic boundaries and system hierarchy. Organizing the system with a geographic scope and system hierarchy is beneficial because of the spatial expanse of most systems, the multi-jurisdictional nature, and the system design. Addressing the scope and hierarchy help organize the simplified structure and also set up analysis results for targeted use. How the system is cropped must be communicated to ensure clarity of what the analysis represents. In the case of series systems a failure anywhere in a system results in failure. A failure hundreds of miles away or the service connection at the street can result in outages. Portions outside the bounds of the assessments should be recognized and noted that their risk is not included in the study.

Setting a geographic scope can help for systems that cover large areas. In urbanized regions most lifelines draw/import water, power, and fuel from sources hundreds of miles away. Some of those systems are even global and could be impacted by events on other continents. Drawing a line geographically around the study is needed for feasibility; this must be communicated clearly when presenting the results. Some systems are easier than others to bound geographically. When a system has storage built into it (reservoirs, tanks) those nodes become ideal places to draw lines around the analysis. Not only do these nodes offer a good place to bound analysis, but they are also a beneficial system characteristic. *Islanding* risk in a system, often by means of a storage facility, prevents the failure of one segment from affecting another (ABAG, 2013b). Water systems in California lend themselves nicely to bounding geographically. Rather than studying the entire water system at once, a supply analysis can study vulnerabilities from the watershed in the Sierra, to a reservoir in a local jurisdiction. A secondary

assessment can then examine vulnerabilities from the reservoir to a specific location, or down to a specific hierarchical level. This is exactly what the San Francisco Public Utilities Commission (SFPUC) did in a system analysis and 4.6 billion dollar water system improvement program (SPFUC, 2013). They studied their system from the Hetch Hetchy reservoir in the Sierra to local reservoirs and addressed vulnerability in that section of the system in order to provide greater water reliability to customers. Another assessment is planned to address risk between the local reservoirs to user portion of the system. By setting a geographic bound they were able to focus on a feasible portion of the system.

The SFPUC study and subsequent system improvement program was extremely beneficial for their wholesale customers. 27 water districts purchase water from SFPUC and distribute to their customers (SFPUC, 2011). Prior to SFPUC's study had one of the local utilities desired to complete a risk assessment they would have had to undertake a study to understand SFPUC's regional water system. Now with the study available, and the seismic risk in that portion of the system largely mitigated, a local municipality can complete a localized study of their distribution system and understand the risk from source to use. Other jurisdictions are not as fortunate. In California many are reliant on other expansive water projects but few have assessments available, leaving local municipalities in the dark unable to measure their comprehensive risk.

Sometimes the upper and lower bounds of a system are not best drawn by a geographic or jurisdictional boundary. When systems don't have storage nodes built in (electrical, transportation, communication) system bounds may be based on hierarchy. A hierarchy can be used to organize a system into binned sections. The hierarchy of

lifelines can often be broken down based on transmission levels measured by volume, size, or number of users. This can be used to set bounds around a system, and it can be especially helpful when setting a lower bound for system assessment. For most assessments it is unlikely the studies resolution will extend down to service connections or the lowest hierarchy of distribution networks. In addition to using the systems hierarchy to set a lower bound, the *distance to* metric of acceptance curves can help set a lower bound and simplify the system further. This requires the assessment to trace lifeline performance such that stakeholders are a unique distance (specified by the stakeholder) away from the system.

When the acceptance of the distance to service is known the lower bound of the system assessment can be thoughtfully considered. If stakeholders admit it acceptable to be a few blocks from a resource this can appropriately reduce resolution of the study. The greatest benefit of the acceptance curves however is in understanding the relationship between the length stakeholders can be without a certain lifeline and the repair times associated with each system component. If system components can be easily repaired prior to the critical point being reached, then they are not very significant to the study. To do this the expected repair times of system components must be known. Orders of magnitude can go a long way; will the component require 1 hour, 1 day, 1 week, 1 month, or 1 year to repair. A number of different resources can help determine these values. Past disasters can provide insight into repair time as can the restoration following small interruptions caused by winter storms or contained accidents. Some systems may have protocols that can be used to determine what damage level results in certain repair times. With this information system components that do not significantly impact the

restoration can be removed from the analysis. As mentioned in Chapter 1, when the stakeholder is very reliant on infrastructure systems and catastrophic losses occur almost immediately, the methodology is unhelpful; however if catastrophic loses occur days, weeks or even months after an event this can greatly simplify the system. Figure 3.4 illustrates this by viewing a hypothetical system through the lens of a stakeholder, filtering and simplifying the system. Systems can be simplified to critical nodes and links by understanding what portions of the system govern the recovery times critical to stakeholders.

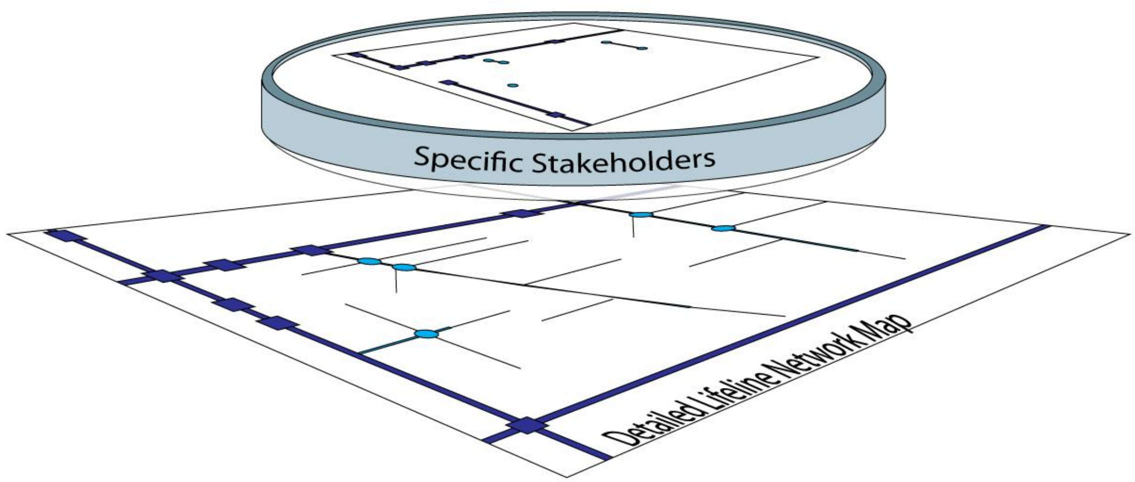


Figure 3.4: Simplifying Lifeline Systems Using a Stakeholder Lens.

By using the stakeholder bounds and using scope and hierarchy to define boundaries, system assessments can be simplified. Not all millions of miles of road or pipeline is going to be mapped or analyzed. It's infeasible and also unimportant. With the system simplified, an analysis can be performed using probabilistic variables originally discussed in Section 2.3.

3.4 Addressing System Probability Variables

In Section 2.3 five variables were discussed that impact system performance and system analysis: multiple damage states, hazards, correlation, system structure, and interdependencies. In a theoretical world these variables can be inserted into probabilistic equations to account for their influence; however, in the real world where ideal variables and attributes are often unknown, solutions must reflect the imperfect data. Variables are explored to determine how they influence a simplified assessment and how they can be used to either further improve or further simplify the assessment.

3.4.1 Multiple Damage States

Developing methods of decreasing states makes the problem easier to analyze. Analyzing multi-state systems as dual-state systems limits the damage states of interest. Electrical systems are already dual state systems, they are on or they are off. Transportation systems, especially roads, are a multi-state system. To reduce the number of states, the consequences outlined by stakeholders can change the level of service measurement, such that the system is converted into a two state system of working or not working. Using transportation networks as an example, travel time from A to B can become the governing variable of the system. Rather than studying the multiple damage states as complete access, limited lanes, etc., the states become commute time less than or greater than a defined number of hours. Travel time doesn't have to be the only measurement used for roadways. For a highway corridor near a port that is critical for goods movement having a route capable of supporting trucks of a certain weight could become the governing factor. In the Maule, Chile event a number of bridges remained

open but were restricted to vehicles less than five tons (Schanack et al. 2012) due to minor damage. For port related access routes this would represent failure regardless of the travel time.

3.4.2 Hazards

Applying hazards to analysis presents difficult methodological choices and offers further opportunity to expand or simplify analysis. As discussed in Section 2.3.3 there are both probabilistic hazard maps and deterministic scenario hazard maps. When analyzing a single facility, probabilistic hazard maps are used to aggregate the risk of all event scenarios, making them a very attractive resource for analysis. This does not work well for systems when an understanding of the whole system performance for discrete events is desired. If probabilistic hazard maps were used for lifelines it would provide insight into the probability of failure of each node and link, but would not provide any insight into the overall system performance in an event. For this reason, when the system performance is the desired outcome, using discrete scenarios provides a greater tool for analysis. The downside to analyzing systems with scenarios is in order to consider the complete risk, hundreds of different scenarios would have to be applied to the system; different faults, ruptures, and sizes, an infeasible option.

In addition to the thinning of the infrastructure data in Section 3.3, reducing the hazard data can be equally important. In regions with multiple faults, or multiple hazards, different events are likely to result in drastically different lifeline performance, especially for spatially dispersed systems which cross or come close to a number of different faults. A seismic deaggregation map of the region may help to determine which

faults are most significant for the lifeline system. This can be difficult as different portions of the system or different lifeline systems all together may be more or less susceptible to different fault events. Again a hierarchical system can be used to thin earthquake scenarios. Some faults are likely to cause regional damage, while others may only cause localized damage. Small events may have a severe impact on infrastructure very near the event, but in these situations all response resources can be allocated to a single site. The ‘big ones’ are unique in that damage will be widespread and resources will be diffused over wide areas. There are cases where smaller events should be considered; for instance when a hazard interacts with a portion of the system that is non-redundant, or a portion that is not quickly repairable. The most basic study will simply examine a single scenario, while more complete studies will consider a handful of different scenarios.

In addition to minimizing the number of scenarios used, matching system components to relevant hazards can also limit the number of interactions studied. Components of some systems are more vulnerable to certain hazards than others. For example, road networks are largely comprised of bridges and roadways. Damage to bridges can be caused by shaking, liquefaction, and fault rupture. Roadways on the other hand are largely damaged by ground failure (liquefaction, lateral spreading, landslide) and fault rupture. Recognizing roadways are not typically damaged by shaking reduces the number of relationships to study. For many systems certain system components are not susceptible to damage in certain hazard types. Distinguishing between relevant and irrelevant interactions will simplify system assessment.

3.4.3 Correlation

Correlation is a difficult but important variable to account for. Correlation relationships can be included in a number of different manners. Correlation influences both the magnitude of the hazard across space as well as the expected performance of components across a system. Hazard loading and component resistance are examined individually.

3.4.3.1 Hazard Loading

Well-designed probabilistic system assessments include spatial correlation to capture similarities in shaking levels and soil conditions across neighboring locations. When using scenarios however, the shaking contours already capture these affects and no spatial correlation factor for hazard loading is needed. Many scenario-earthquake-shaking-maps produced by the USGS include the influence of topography, soil, and fault mechanics. When using the simplified method, correlation as it relates to the hazard need not be included because scenarios are used. The magnitude of the hazard across space is part of the scenario and spatial correlation can be omitted. Interstate 280 along the Peninsula of the Bay Area is used as an example.

In the Bay Area Interstate 280 and Highway 101 run North South along the Peninsula. The parallel highways are also parallel to the San Andreas Fault. Interstate 280 is a quarter to one mile from the San Andreas Fault with 101 just a few miles further East. Because 280 runs parallel with the fault, the scenario shaking in a San Andreas event results in most bridges along the corridor experiencing the same MMI shaking

intensity (see Figure 3.5). Considering only shaking intensities no spatial correlation is necessary to understand the loading along the corridor. By using a discrete scenario it is addressed already.

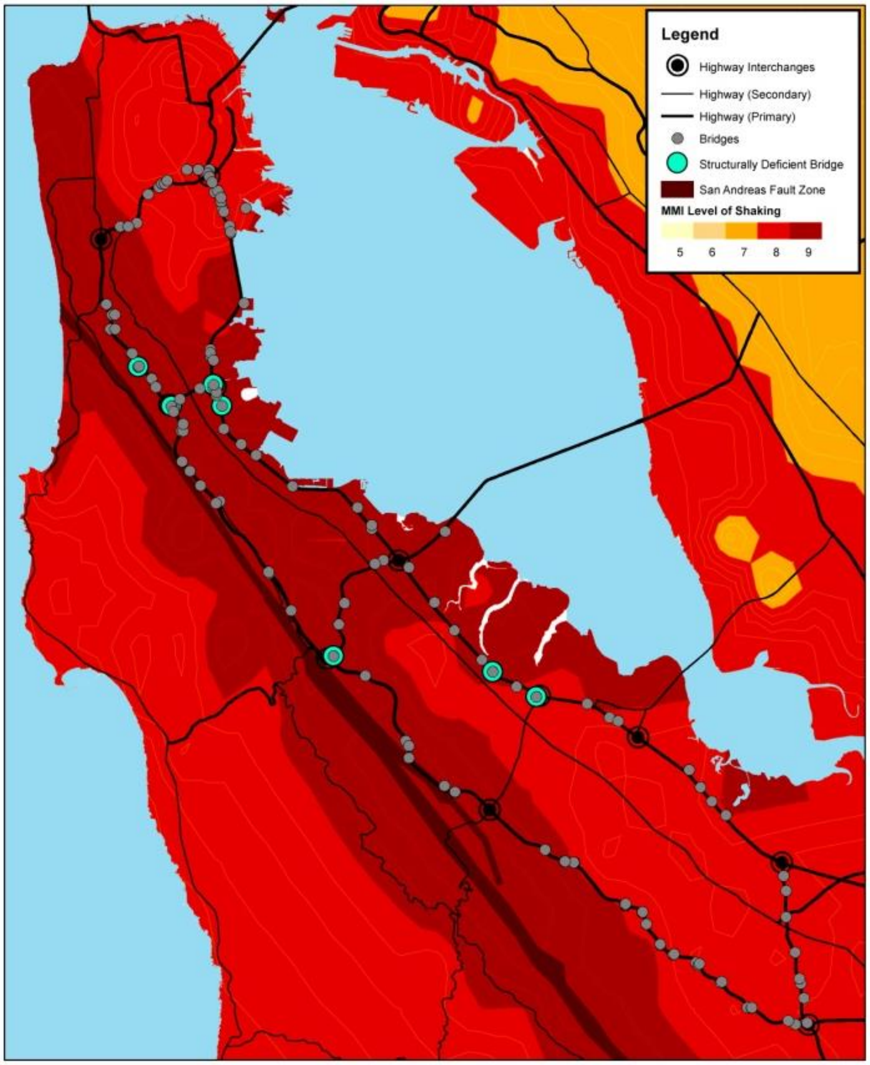


Figure 3.5: Highway Network Exposure in a M7.9 San Andreas Scenario.

Unfortunately, this map only explores the shaking intensity hazard, not secondary hazards like landslide or liquefaction. Most jurisdictions only have scenario earthquake

hazard maps that show shaking intensity. There are separate hazard maps for secondary hazards like liquefaction and landslide that are not scenario based. Understanding the relationships between hazards is very important for the simplified method, i.e. if severe shaking here, then likely liquefaction/landslide there. This need is illustrated again by the Interstate 280 example along the Peninsula in the Bay Area, this time including liquefaction hazard.

Over the same stretch of peninsula that 280 runs near the San Andreas Fault, Highway 101 simultaneously passes over a very high liquefaction susceptibility zone (see Figure 3.6). Highway 101 along this stretch is often less than a mile from the San Francisco Bay, and is equidistant from the San Andreas fault resulting in fairly uniform shaking. It is assumed that the majority of the liquefaction zone is a result of bay soils and bay fill with similar properties. Given that the loading and soil conditions are similar it can be expected in a San Andreas event with fault rupture along the Peninsula if liquefaction occurs at one location on Highway 101, it is likely to occur along many portions of the Highway.

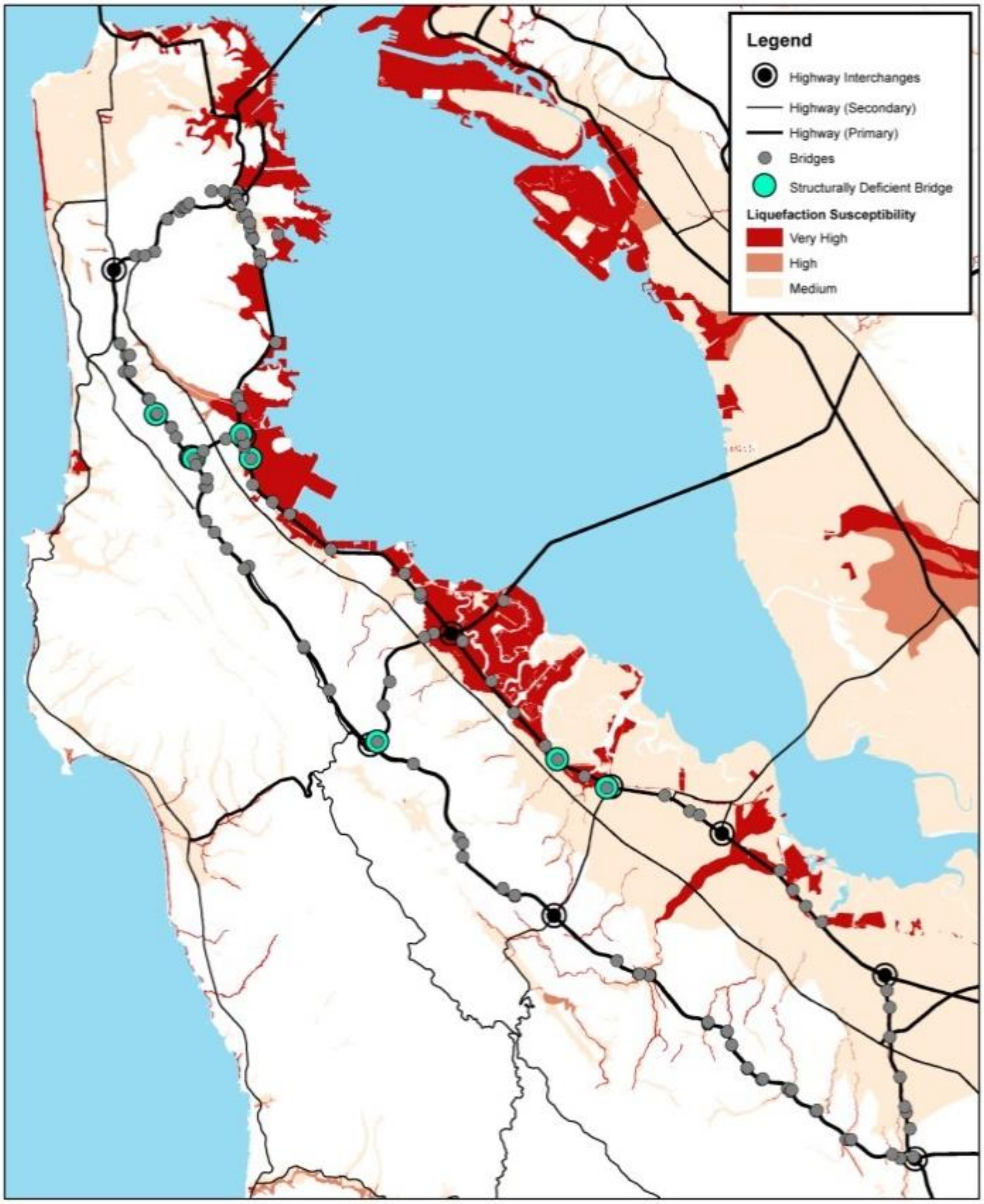


Figure 3.6: Highway Network Liquefaction Susceptibility Exposure.

What is of more importance is the relationship between shaking levels at bridges on Interstate 280 and liquefaction susceptibility along corresponding portions of Highway

101. Understanding the correlation between shaking along 280 and liquefaction along 101 would be a valuable relationship to understand.

More study is needed on the correlation between hazards. It is unclear what MMI 9 shaking along the 280 corridor means for liquefaction probability along the 101 corridor. One possible method may match shaking intensity levels of a scenario with different liquefaction/landslide susceptibility zones. While this is less than an ideal scenario, at a very simplified level one might be able to overlay a liquefaction or landslide susceptibility map with scenario shaking levels to create a map more appropriate for an individual scenario. Before using this approach further study is required to determine appropriate relationships, i.e. in liquefaction susceptibility zones less than MMI 5 result in very low risk of liquefaction, while in MMI 8 and greater there is a significant risk of liquefaction.

Despite current uncertainty in how to address correlation between hazards, this risk should still be communicated in some form. The Interstate 280 and Highway 101 example illustrates the importance of considering both hazards to examine the performance of the transportation network along the Peninsula.

3.4.3.2 Component Resistance

Most systems are made up of many links and nodes that are designed similarly. When studying the relationship between components there are an endless number of characteristics that could be correlated. Determining which component characteristics

have significant correlation is key in focusing study on characteristics that will influence system performance.

Many probability textbooks discuss correlation with examples of factory produced widgets that are nearly identical replicas and thusly perform similarly. While real world system components may not come from a widget factory, may components are similar and serve the same function. Take for example bridges. A bridge is designed to get people and things from A to B. There are a range of structural systems (cantilever, truss, suspension, etc.), materials (steel, concrete, composite, etc.), sizes (# of spans, # of lanes), ages, and other distinguishing factors. Each characteristic is likely to have some value of positive correlation between two like bridges. In a city or region with hundreds or even thousands of bridges there are likely bridges that will perform similarly under similar loading. But with components like bridges, any of the attributes above could be correlated. Narrowing down the list is necessary for a simplified study. A components age stands out as a good correlation characteristic to study.

Age is an attractive attribute to study because it is a good proxy for the code used, as well as the degradation due to use and environmental conditions. It can also be a good indicator of material for systems that underwent changes for one reason or another. For instance, the age of pipe often informs the material used and the fabrication method. Examining past earthquakes is critical for the study of correlation across like system components. Drawing correlation relationships of past performances aides in the prediction of future events. Following the Northridge earthquake statistical breakdown of bridge damage showed that bridges designed with older standards were more prone to damage (Basoz, Kiremidjian, King & Law, 1999). The more recent 2010 Maule

earthquake in Chile reinforced this pattern when 12 piers and 22 spans of the 70 year old Bio Bio bridge in Concepcion collapsed (Schanack et al. 2012). A new bridge parallel to the old one experienced nearly identical forces but had minor repairable damage.

Age as the primary correlation attribute was considered with strictly developed nations in mind, where a code is applied to all development, and where there is oversight to ensure that what is designed is constructed. Chile, a country with an enforced code, is a good example. In the 2010 earthquake, minor damage was consistent across all bridges, "almost all of the 100 bridges visited during the field investigation in March 2010 exhibited expansion joint failure and stopper damage, but they remained operational," (Schanack et al. 2012). Because they all followed the same code most bridges had similar damage states. If changes are made to a future code, the age of bridges pre and post Maule earthquake may be likely indicators of this minor damage. Age may be an inappropriate measure of correlation for countries with less engineering and construction oversight. In developing nations other characteristics may have stronger correlation relationships.

In an ideal world with reliable data to insert into probabilistic system analyses multiple factors could be included in the correlation between components. In the real world both data and resources (time and money) are often insufficient to obtain the data for complete detailed analyses. When variables like age are known studying its utility as a proxy for other variables and understanding its correlation significance can offer some added insight to improve the analysis performed.

The simplified method relies on using scenario hazard data and making the most of available system attribute data. Past earthquakes offer insights into correlation, but greater study is needed to account for correlation beyond elementary discussion.

3.4.4 Interdependence

When using the simplified assessment focused on catastrophic risk some interdependencies become less significant while others have greater influence. Most research lumps interdependencies as a single characteristic, but when considering the simplified methodology it is important to distinguish minute differences between types of interdependencies which I define and provide examples of. Table 3.1 lists the different types of interdependency and their significance when using the simplified methodology.

Table 3.1: Significance of Different Types of Interdependence

Signficance	Interdependency
Less	Cascading Outages
Same	Cascading Failures
More	Influence on Recovery
More	Multi-System Processes

3.4.4.1 Cascading Outages & Cascading Failure

There is a minute difference between these two types of interdependencies. Cascading outages occur when one system fails because it is reliant on another system that has failed. The cascade does not cause any physical damage that requires repair, it simply requires the other system to be restored, or for backup resources to be applied. Cascading failures are different and occur when one system incurs physical damage

because of the interruption of another system that has failed. The cascade causes physical damage that requires repair. A system that was damaged by cascading failure, is reliant on its own repair and the restoration of the other system.

These two types of interdependencies have been well documented in Section 2.2 and Section 2.3. Cascading outages are less significant because they often represent interruptions in service that are not of catastrophic nature. Directly following any significant earthquake every system will experience a number of cascading outages. Cascading outages have a very significant effect on lifeline performance hours and days into an event, but are infrequently responsible for longer catastrophic outages. Cascading failures remain important as they are needed to fully measure the damage that requires repair. A complete study will recognize interdependencies that cause physical damage to one system when another fails.

3.4.4.2 Influence Recovery

Understanding interdependencies during system restoration is important when using a methodology that attempts to understand a components repair time. Recognizing interdependencies during repair will more accurately represent the time required for systems to recover, and also introduces new opportunities to mitigate or prepare. The Bay Area Peninsula example used in Section 3.4.3 can be studied further to consider how interdependence influences the repair of systems. Should liquefaction occur along Highway 101, access to asphalt will be a governing factor of roadway restoration. There are only a handful of asphalt plants on the peninsula, all of which have portions of their facility in liquefiable zones, and all of which rely on natural gas to produce asphalt. If

the roads need asphalt to repair liquefaction damage, there is a chance asphalt plants were also damaged by liquefaction, and/or there is damage to the natural gas line which runs adjacent to 101 and fuels the asphalt plant. It's important to consider if certain damage occurs to one lifeline what other facilities, lifelines, and resources are involved in restoration, and if their failure is correlated to the damage experienced by interrupted lifeline.

3.4.4.3 Multi System Process

Most basic processes require multiple lifelines for tasks to be completed. As mentioned at the end of Section 3.2, when considering each lifeline it is important to consider the processes that they are accomplishing, and the degree to which their probability of failure is reliant on intersected lifelines. When assessing all systems within a region, studying the differences in system performance may reveal unacceptable risks, and/or may reveal unique mitigation solutions. To illustrate this, the relationship between the fuel sector and transportation sector described in Section 3.2 is expanded upon to consider commuting options for professional sector stakeholders.

In the professional sector telecommuting may be an acceptable commute option for employees. For stakeholders where this is the case, commuting can occur by physically commuting, or by using communications platforms to work from home. If either commuting option is acceptable only one needs to be available for failure to be avoided. When both are unavailable there is a commuting outage. This can be described probabilistically using venn diagrams. The venn diagrams in Figure 3.7 represent a hypothetical scenario but illustrate relationships seen in past earthquakes. The boxes

beneath each venn diagram attempt to illustrate how early on vehicle transportation may be a more reliable commute option, but very quickly telecommuting becomes a more likely option. In the boxes, green signifies either option is available, yellow one of the two commuting options is available and red means neither. For a business where either commute option is acceptable, limiting the amount of red is the priority, especially when the critical point in time is reached.

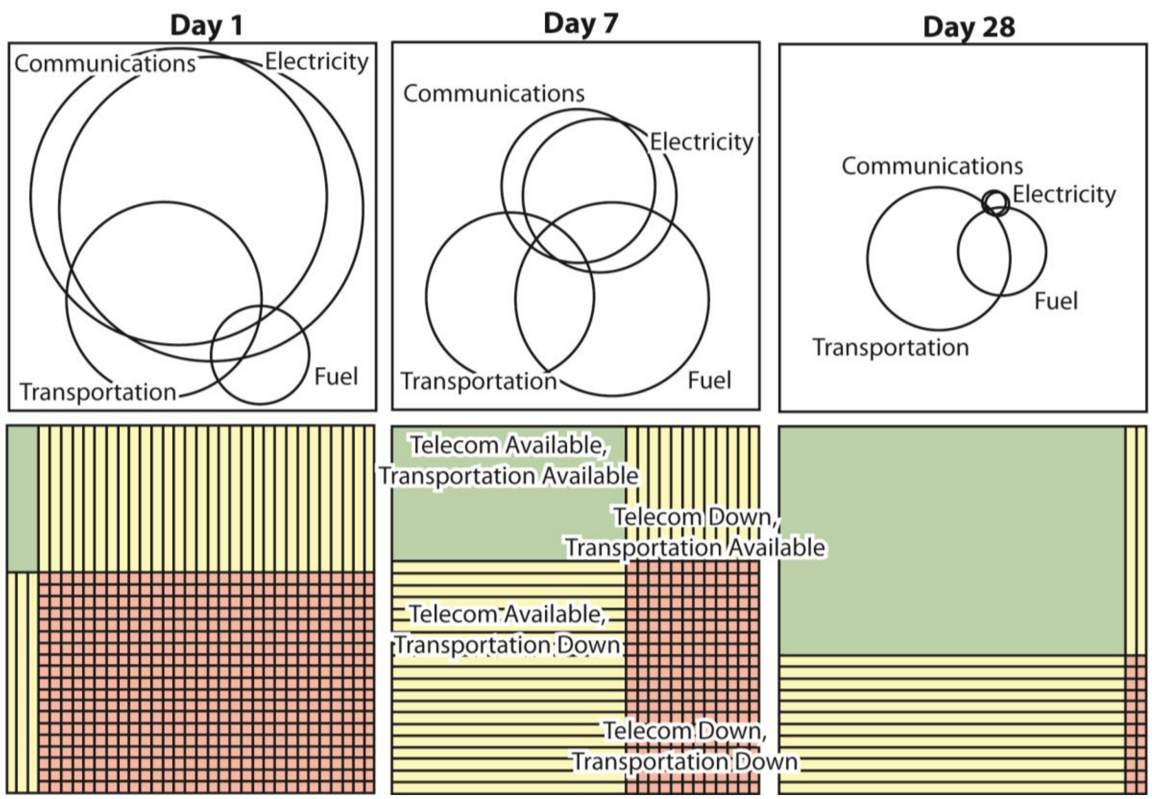


Figure 3.7: Probability of Outage Displayed with Hypothetical Venn Diagrams 1 Day, 7 Days, and 28 Days After a Major Event.

It is common in many earthquakes for there to be disruptions immediately following an event in electrical and communications systems; however, these two

systems are often the most rapid to restore services and their systems are highly interdependent both in failure and recovery. Many communication outages are a result of no electricity (cascading outage) or they are both collocated along the same pole, so when the restoration of one occurs the other is often restored at the same time or soon after. This is reflected in the venn diagram with both electric and communication systems having similar probability of failures across time, and large intersections where they are both out, or both on. Transportation and fuel are different. Unlike electrical and communication systems the performance of the transportation system is likely not well correlated to the performance of the fuel network, and their restoration is less interdependent. Because their restorations are not linked, the significant failure of one system can disrupt physical commutes despite the acceptable performance of the other. Transportation is shown in the Venn diagrams as a moderate risk to fail, but if failure does occur, the system often requires weeks and months to repair. Fuel is a system that has not been studied comprehensively. It may be expected initially for there to be no outage because people have inherent fuel storage in their vehicles; uniquely, the fuel shortage as shown in the graphic may increase a week into an event. If the transportation and fuel systems are damaged, past events have shown these systems require a much longer time to restore compared with electrical and communication systems.

Stepping back and looking at the venn diagrams and their paired boxes reveals that while the probability of failure for electrical and communication systems can be large, their failures largely intersect. For the transportation and fuel system the intersection is much smaller resulting in a greater overall probability of failure for the process of physical commuting. Understanding these relationships in greater detail will

more accurately measure the risk for important stakeholder processes and may result in more appropriate and balanced mitigation solutions. Chapter 5 will explore mitigation solutions and issues in greater detail. For the example above a single organization may be unable to mitigate transportation failures, but increasing the robustness of their communications system may decrease their telecommunications vulnerability and decrease their reliance on transportation and fuel lifelines.

3.5 Summary

Developing a complete lifeline risk assessment would provide the best resource for decision making; however, a complete assessment is infeasible for most systems. Rather than solving for all possible lifeline outage scenarios and then discussing the impact of various outages on businesses, the process can be reversed to focus on consequence first. Consequences are measured by lifeline users and then used to simplify system components that govern restoration. Using this simplified methodology provides an understanding of catastrophic risk which can be used by stakeholders to address vulnerabilities that impact their resilience.

4 BAY AREA FUEL SYSTEM CASE STUDY

"Everyone thinks they have a #1 ticket. You're going to need another plan." – Tom Collins

Following the steps outlined in Chapter 3, the Bay Area fuel system is used to demonstrate the proposed methodology. California Energy Commission reports, fuel industry websites, earthquake reconnaissance reports and technical papers were used to determine stakeholder reliance on fuel, geographically map the system, understand the fuel sector processes, understand the fragility of system components, and then perform a system simplification and monte carlo simulation of key system components. The chapter is broken in six sections:

- Section 4.1 a variety of potential bounding stakeholders are explored.
- Section 4.2 the greater public is used to set a critical point to simplify analysis, using estimated acceptance curves.
- Section 4.3 describes the Bay Area fuel system as well as its exposure to specific events.
- Section 4.4 explores system component fragilities as well as restoration timelines in past events.
- Section 4.5 uses fault trees to show the simplification of system analysis. A monte carlo simulation is used to calculate the risk to the portions of the system that contribute to the Bay Area's catastrophic fuel risk.
- Section 4.6 summarizes the process and how the results of the study can be used to inform decision making.

All the data was gathered from publically available sources. Portions of this case study are included as part of a greater Bay Area infrastructure assessment performed for the

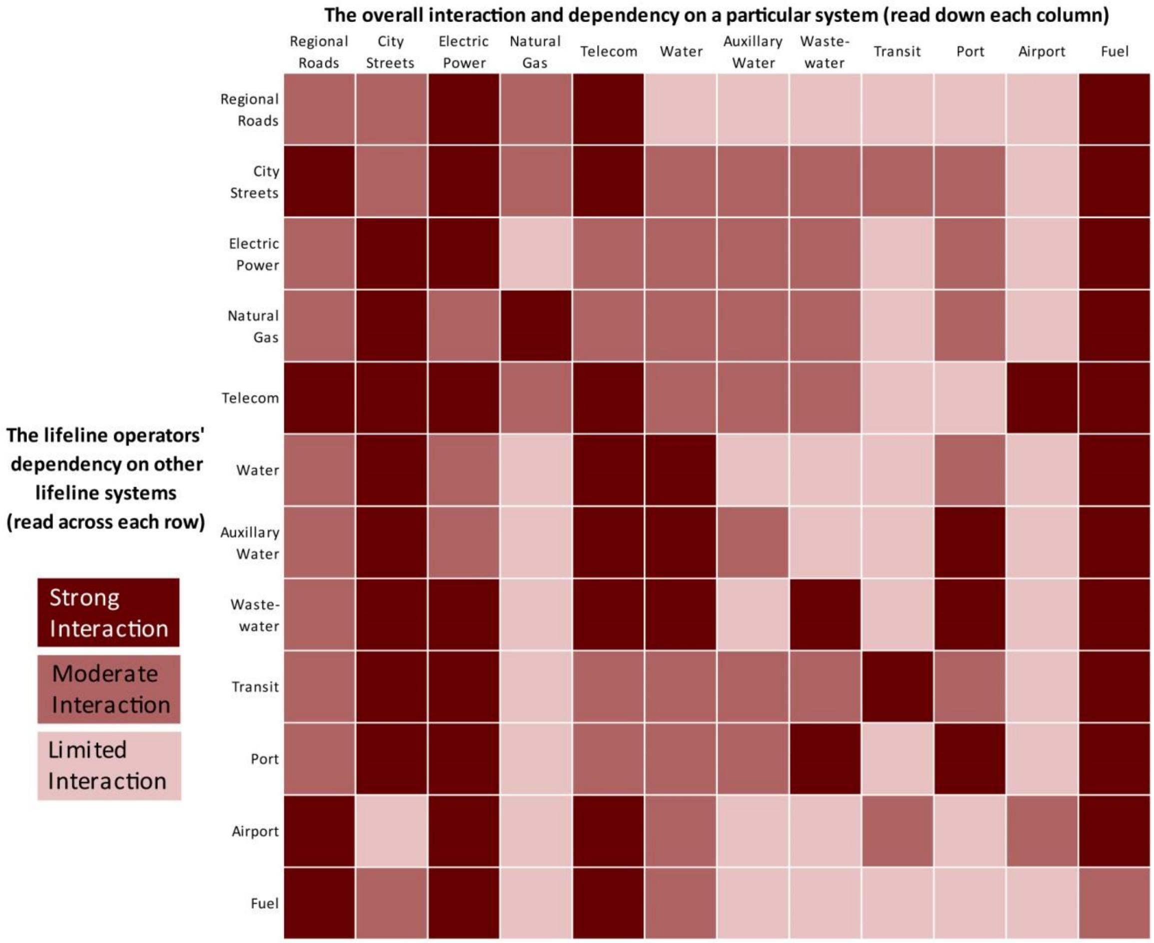
Association of Bay Area Governments (Appendix B), which includes assessments of the region's transportation, water, and energy sectors.

4.1 Stakeholders

A study of Bay Area fuel could be performed for a number of stakeholders. The companies that own and operate fuel system processes have an obvious interest in the vulnerability of their assets, but so do the customers reliant on fuel. Utilities, government, institutions, and the general public are all reliant on fuel for their day to day and post-earthquake operations. An assessment designed for the fuel industry would focus heavily on direct losses. Exploring the impact of the fuel system on users provides a better stakeholder group to apply the theorized methodology and provides information to users unaware of the risk.

There are many stakeholder groups that are users of fuel. Narrowing the stakeholder group down will make the assessment easier. Utilities are an attractive audience because the results could help them address issues of interdependence. For most utilities their day to day operations are no more reliant on fuel than any other sector. However in post-earthquake operations fuel can become a critical resource. In past earthquakes like Loma Prieta utilities experienced cascading failures when they lost electricity; water pumping stations stopped, communication systems powered down, and critical facilities were in the dark. Since then many have purchased generators to supply power in the event electricity goes out again; however, for these generators to run, fuel is needed. In a 2013 workshop with Bay Area utilities nearly all participants (water, wastewater, power, and transportation) agreed fuel was their greatest interdependency (UASI, 2014). A 2014 interdependencies study commissioned by the San Francisco

Lifelines council echoed these results. As part of the study each utility that services the City and County of San Francisco was interviewed and asked which systems they are reliant on. Figure 4.1, a matrix from the councils Lifelines Interdependencies Study, shows that every other utility in the region is significantly dependent on the fuel sector (San Francisco Lifelines Council, 2014). In addition to using fuel to run generators at critical facilities, the vehicle fleets used to repair broken systems often only have a few days volume of normal operations fuel on hand. In the utilities workshop many acknowledged operations would not be business as usual. Around the clock work and outfitting mutual aid resources would deplete fuel stocks quickly. For most utilities a fuel outage of any length could be deleterious to the system and restoration efforts.



Reading the matrix from left-to-right shows which systems the designated operator relies on. For example, Airports have a strong interaction with regional roads, but a limited interaction with natural gas.
Reading the matrix from top-to-bottom shows which systems rely on the designated operator. For example, all systems have a strong interaction with the fuel system.

Figure 4.1 San Francisco Lifelines Interdependencies Matrix.

The general public is also reliant on fuel. In the nine counties that touch the San Francisco Bay nearly 7 million gallons of fuel is exhausted daily, see Table 4.1. Personal vehicles represent nearly 80% of the work commute transportation mode split, shown in Table 4.2. Another 10% use public transit of which a portion requires fuel. In order for businesses to function and communities to recover from an earthquake, fuel will be an important resource without which the Bay Area would come to a standstill.

Table 4.1: 2011 Average Daily Fuel Sales in the Nine Bay Area Counties (Gallons)

County	Gasoline	Diesel
Alameda	1,501,370	76,712
Contra Costa	1,082,192	57,534
Marin	282,192	8,219
Napa	128,767	5,479
San Francisco	413,699	8,219
San Mateo	849,315	27,397
Santa Clara	1,893,151	76,712
Solano	597,260	54,795
Sonoma	487,671	52,055
Bay Area Total	7,235,616	367,123

California Energy Commission, Energy Almanac (2011)

Table 4.2: 2012 Transportation Mode Split for Nine Bay Area Counties

Transportation Mode	# of Workers	% of Total
Drove alone	2,305,119	67%
Carpooled	359,908	10%
Public transportation	369,358	11%
Walked	119,375	3%
Other means	109,486	3%
Worked at home	193,642	6%
Workers 16 years and over	3,456,888	100%

American Community Survey, Selected Economic Characteristics (2012)

A study for all fuel users would require a very comprehensive study, one that explores fuel availability in the days and weeks after the earthquake. The proposed methodology is unhelpful in understanding fuel availability in the days after the event. While utilities are an important group to consider, they cannot be included as a stakeholder for this study because they in essence require access to fuel without interruption. Their operations should be considered similar to a hospital, and should be treated as such during the response to a disaster. To simplify the problem this study will use the impact of fuel interruption on institutions and the general public. These groups

are used to frame the study using time, quality, quantity, and distance acceptance measures. The acceptance curve for the Bay Area will be assumed with the basis of regional resilience in mind – considering the fuel needs of the masses, not the outliers. With that in mind the four scales discussed in Section 3.2 are considered.

4.2 Acceptance Curves

The fuel system offers a textbook example of the four scales of user acceptance: time, quantity, quality, and space. Fuel as a commodity can be understood by each of these dimensions of acceptance, and as one dimension changes it has an impact on the others – they are all interrelated. All four dimensions are used to understand at what level of service the system will cause catastrophic losses for the region.

Time. The length of an outage will impact each business or individual slightly differently. Fuel is unique in that typically some is stored in vehicle tanks. In addition to individuals having fuel stored within their own vehicle, gas stations store fuel in large underground fuel tanks, as do pipeline terminal stations. Because of the inherent storage for most, a fuel outage will not begin directly following the event, there will likely be a lag for all stakeholders. Setting an outage time is tricky because of the lag, the ability to store, and the other three acceptance scales all impacting the effect of the outage. The amount of refined fuel stored in the region fluctuates and is not publicly available at the regional scale, however, the State of California keeps a record of how much fuel is stored each month. The average reformulated fuel stored in the State of California in 2013 was 5,600,000 barrels (CEC, 2011). If you make the assumption that the fuel is stored proportionately to population across the state, the Bay Area would have just over one

million barrels of stored fuel, which corresponds to one week of average fuel use. Even if Northern California had a disproportionate amount of stored fuel compared to Southern California, the storage would likely not exceed two weeks.

Before a critical point with respect to time can be set, the other acceptance scales must be considered. Other factors like long-term population evacuation, rationing, and behavior change will all impact where the critical point is set for the region.

Quantity. Adjusting the quantity of fuel available can drastically extend the acceptance of a shortage. There are substantial improvements if people are provided with *some* fuel; enough fuel to make trips to relief distribution points, enough to fuel public transit systems, or enough fuel to commute to work a fraction of days. Fuel rationing is a useful policy following disasters to provide a limited amount of fuel to all users. Upwards of three weeks after Hurricane Sandy a fuel shortage persisted that hindered recovery efforts and contributed to a lingering delay in people resuming daily life operations (Sandalow, 2012). Because of the shortage in many communities fuel rationing was instituted. The acceptable time without regular fuel conditions can be extended if rationing protocols are established. For this analysis we will assume strong fuel rationing will take place if a major earthquake impacts the fuel system – resulting in a quarter of the demand.

Quality. There are some unique cases to California that should be considered. Fuel in California is a special grade to limit air pollution. Under normal conditions fuel used in other countries and other states cannot be used in California because it does not meet the California reformulated gasoline (CARFG) standards. The fuel grade in California has additional blending components that are typically included at the refinery,

and also requires additional ethanol to be added at distribution terminals (Schremp, 2013). In the event that there was significant damage to the refineries there would be regulation hurdles to suspend before imported refined fuel could be used. In the event of a fuel emergency, fuel waivers would enable the use of other fuels. Both the US Environmental Protection Agency (EPA) and California Air Resources Board (CARB) would need to be involved (Schremp, 2013)

In addition to the quality of the fuel, the quality of the service can also be considered. People may be willing to wait 20 minutes in a line to refuel, but likely not hours. Just as rationing alleviates quantity issues it could also improve the service quality in terms of wait time.

Space. Distance to fuel poses another interesting issue. In the event that fuel was distributed at fewer locations than currently exist, it could pose a unique problem in which people are using a large percentage of their fuel to refuel. One pharmaceutical supplier in the aftermath of Katrina had to convoy its distribution trucks with a fuel truck to get supplies into and out of the region. Without a fuel truck the pharmaceutical supply trucks would have been unable to complete a round trip without coming across a service station with fuel (Collins, 2013). As will be discussed in the next section, portions of the fuel system are responsible for pumping fuel across the region and northern half of the state. If this portion of the system fails, space becomes a key quality of concern. For this analysis it is assumed that fuel must reach at a minimum the major fuel terminal facilities, described in Section 4.3 and mapped in Figure 4.2.

With these four dimensions in mind, and for the distinct purposes of testing the methodology, a time period of two months when 50% of the refineries are

nonoperational, and six months when 33% of refineries are nonoperational. This assumes emergency fuel supplies are used for key services, some population temporarily leaves the impacted region, severe rationing occurs – greatly altering how the region uses fuel. Lastly, it is important to remember this is a value that assumes the brink of irrecoverable regional losses and is averaged for the masses. Unique institutions may be challenged more or less severely. In the event of a larger study of the fuel system it is important not to skip the step of understand user acceptance curves, but rather to engage key stakeholders, community based organizations, institutions, and local governments to more accurately define what length of outage represents the limit of what the region can withstand.

4.3 System Layout & Bay Area Hazards

The Bay Area is unique in that all phases of the fuel system exist within the region except for the drilling and extraction of crude oil. There are four stages of the fuel system that could be impacted in a Bay Area earthquake: (1) crude oil import, (2) refinement, (3) fuel transmission export, and (4) fuel distribution. The risk for the Bay Area is unique because so many of the processes occur in the region and any interruption in the four phases would cause disruption. A failure in anyone one phase, causes an interruption for the end user. The sequential process to import, refine, transmit, and distribute fuel is a general system. The import, refinement, and distribution stages have parallel components, but the transmission of refined fuel for individual locations is best categorized as a series system.

Crude import occurs by pipeline from the east, rail from the north, and marine tankers from the west. 38% percent of crude oil is piped to the Bay Area from California

oil fields, mainly in Kern County. Another 12% is imported from Alaska and 50% from foreign sources (WSPA, 2013) which arrives mostly on marine tankers. In a few years however a large percentage of the crude oil is likely to be brought in via rail through Solano County from the North.

The San Francisco Bay Area has five refineries located along the San Pablo Bay and the Carquinez Strait, which combined processed 235 million barrels of crude oil in 2012. California as a state processed 595 million barrels of crude oil, utilizing 87.25% of the 682 million barrel capacity. In Figure 4.2 the locations of the refineries as well as their refining capacity are shown. They produce more than twice the fuel the nine Bay Area counties consume, exporting the remainder of the refined fuel across the northern half of the state and elsewhere.

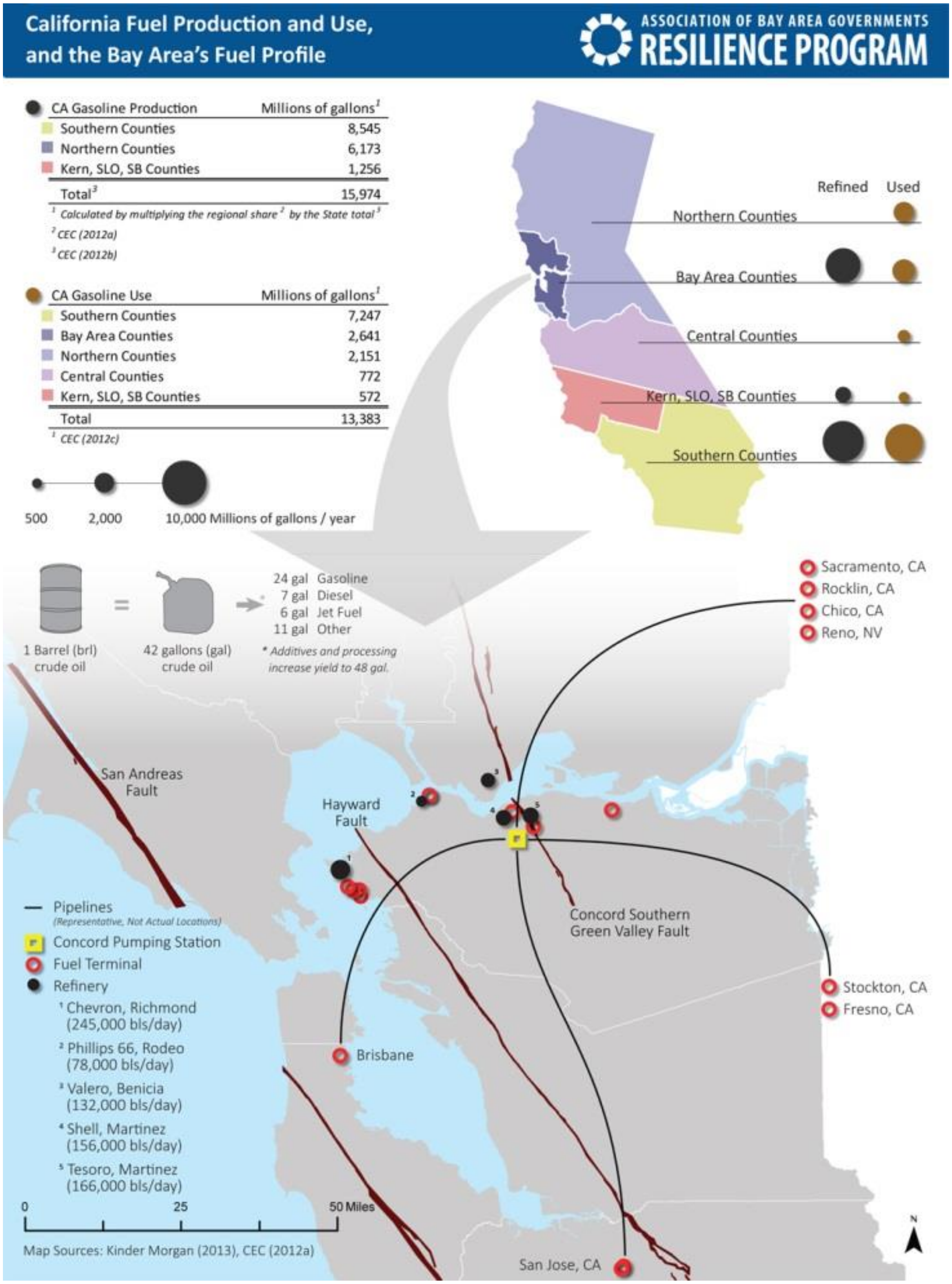


Figure 4.2: The Bay Area Fuel System (ABAG, 2014).

Refined fuel users in Northern California are dependent on the five refineries. There are no refined fuel pipelines that connect Northern California to any refineries outside of the region. All of Northern California and parts of Nevada are supplied by the five Bay Area refineries. In Figure 4.2 the main terminal facilities that receive refined fuel from the Bay Area are mapped. Nearly all of the fuel refined at the five refineries is pumped to Concord, where the Concord Station facility pumps the fuel out to the terminals across the Bay Area and Northern California. At the terminals there is fuel storage and truck loading racks to distribute fuel to local gas stations. Fuel tankers then distribute fuel locally using the road network.

A disruption in a single phase could limit fuel supply in the Bay Area. Interruptions in either of the first two stages would result in fuel shortages. Failures in either of the second two would result in difficult distribution. Both pipelines and refineries are examined to determine their respective fragility to earthquakes.

4.4 System Fragility & Repair

Fuel networks are generally composed of above ground facilities and pipelines. Above ground facilities are vulnerable to the same forces as any other structure. Shaking, ground failure, and fault rupture could all cause significant damage to an above ground facility. These facilities often have intricate routing of pipes and equipment that must also be designed and anchored properly.

> *"For above-ground components of pipeline systems, such as buildings and storage tanks, inertial forces resulting from ground shaking are a major concern,"* (FEMA, 1992).

Pipelines are often buried underground for safety from non-earthquake hazards. In earthquakes the shaking intensity rarely damages pipelines, ground failure is the greatest concern for underground pipelines.

> *"For buried pipelines, inertial forces are of little concern, but faulting, landslides, and liquefaction pose major problems…. Large permanent ground movements caused by surface faulting, soil liquefaction, and landslides are the most troublesome sources of earthquake damage to gas and liquid fuel pipelines,"* (FEMA, 1992).

The majority of fuel literature is focused on natural gas and fuel pipeline vulnerability, with little discussion of node facilities. In particular there has been remarkably little published on the seismic vulnerability of fuel refineries. This is likely in large part because of the infrequent interaction between refineries and significant ground shaking. A closer look at past California earthquakes show that few earthquakes have produced high MMI levels in the areas with refineries, and no earthquake in California in the past 60 years has resulted in MMI values greater than 6 at refineries.

Most refineries in California are clustered in two areas, the Carquinez Strait in the San Francisco Bay Area, and the Long Beach area in Southern California. There are also smaller groupings of refineries in Santa Maria and Bakersfield. The first refinery in California was constructed in Rodeo in 1896. When it first opened, the facility occupied only 22 acres and processed 1,600 barrels of crude oil a day (Phillips 66, 2013). In 1906

when the magnitude 7.8 earthquake ruptured along the Northern San Andreas only two refineries existed in the Bay Area, the Richmond and Rodeo facilities. The earthquake likely produced MMI values of 7 and 8 at the Rodeo and Richmond facilities. Reports from the Richmond Refinery summarize the damage.

> *"The 1906 earthquake damaged the refinery's 40-foot stacks and other equipment, but fortunately took no human toll at the California plant. [The refinery] incurred relatively limited damage, which included the collapse of several brick chimneys, the shattering of a fire wall, the springing of some tank seams, and the snapping of a wharf line,"* (Chevron, 2013).

No reports were found for the Rodeo refinery. This event provides some insight, but the facilities and processes that existed over a century ago are much different than those of the present. Figure 4.3 are pictures from the Richmond Refinery in 1906 and 1907. The refineries that exist today are constructed for different process and scales.

Figure 4.3: Pictures of the Richmond Refinery in 1906 and 1907 (Chevron, 2013).

The only other earthquakes impacting refineries with MMI intensities above 6 were the 1933 Long Beach earthquake and the 1952 Kern County earthquake. The Long Beach earthquake occurred when 5 refineries existed in Southern California, and the

Kern County earthquake shook Bakersfield when there were two refineries in the region. Limited information about refineries was found for the 1933 Long Beach earthquake, but the lack of reported damage could imply damage was minimal. In the Kern County earthquake a few reports and newspaper articles describe refinery damage in Bakersfield. The front page of the newspaper read:

> *"The horizon south-west of here lit up in an eerie glow in the pre-dawn hours yesterday when five 2500-barrel natural gas and butane storage tanks in the Paloma fields erupted with a powerful roar, blanketing the refinery in flames. The initial blast, not unlike an atomic blast, complete with sinister mushroom effect, led people to believe a bomb had been dropped."* (The Bakersfield California, 1952)

There was some structural damage to the refining facility due to earthquake ground shaking, however the majority of the damage was due to an explosion a few minutes after the earthquake (Bergman & Owen, 1952). Beside these three events most other large California earthquakes have occurred a considerable distance from fuel refineries. Figure 4.4 is a timeline of refinery openings (brown circles) broken down by region. Major earthquakes and their estimated MMI shaking intensities at the nearest refinery have also been included to show the limited strong shaking near refineries in CA since the 1952 Kern County earthquake. It has been over 60 years since a California refinery experienced MMI greater than 6.

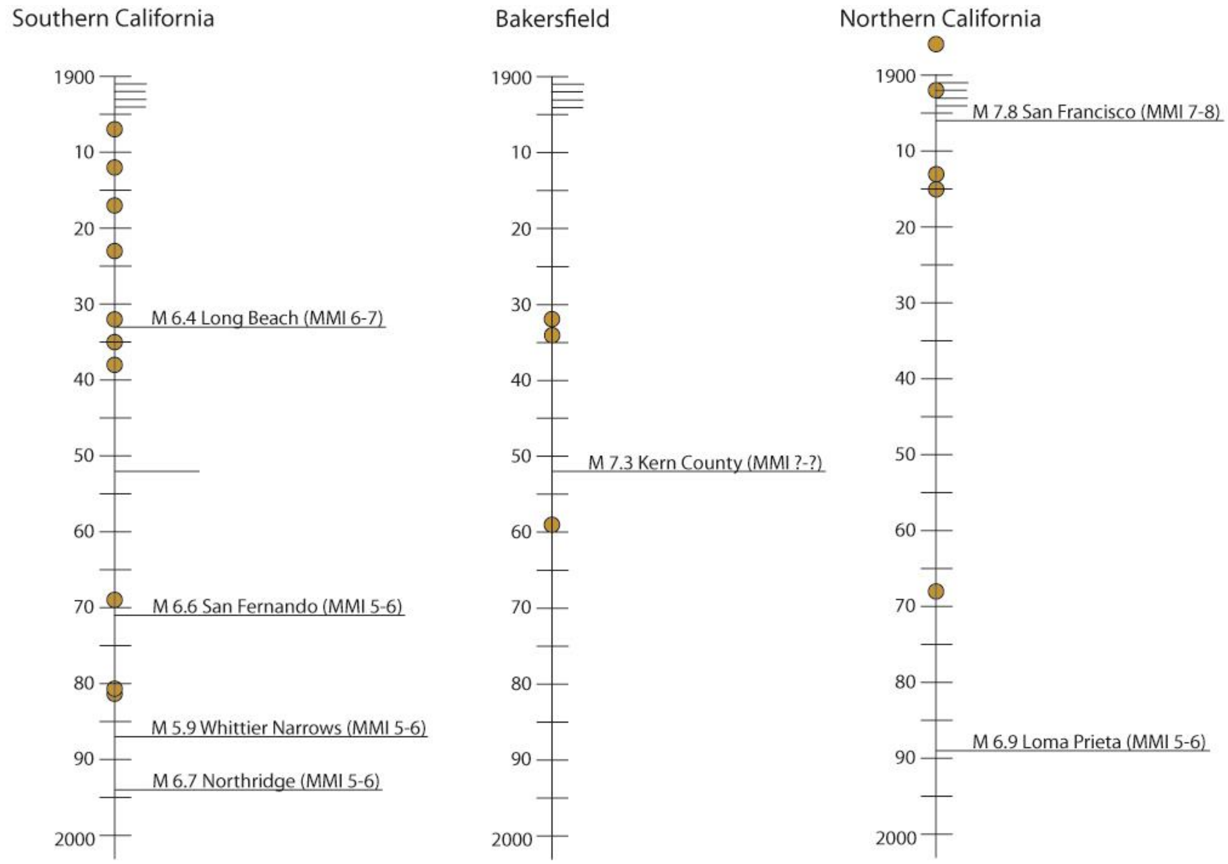


Figure 4.4: Refinery Opening Dates and Major Earthquakes by CA Region.

As with most problems in the earthquake field, more recent earthquakes in other portions of the globe offer the greatest insight into the current level of vulnerability in the United States. Two earthquake events in the past 15 years located near refineries caused significant facility damage. In both cases the refineries were shut down for 3 months before resuming a portion of their original refining.

In 1999, the Kocaeli earthquake caused severe ground shaking in a portion of Turkey with a large industrial sector. Korfez, Turkey's largest refinery was 3 miles from the fault (RMS, 2000), and experienced MMI values of 9-10 (USGS, 2000). The Korfez refinery, 50 miles east of Istanbul, refines 220,000 barrels daily which represents 1/3 of

the nation's oil refining. The refinery was built in 1961 and underwent expansions in the 70's and 80's. It was designed to international standards, similar to most industrial facilities (Johnson, 2002). The Korfez Refinery was damaged in the 1999 Kocaeli earthquake. A fire, mostly centered around the tank farm burnt for three days and was not officially contained for five days. In addition to the fires, there was structural damage to the refinery. Equipment collapsed and damaged neighboring structures and piping. The failures at the refinery were unrelated to the poor construction flaws that resulted in building collapse elsewhere in the country (Johnson, 2002). The damage caused the refinery to close completely for 3 months. During a reconnaissance visit 13 months after the event, the refinery was back to full operation. Over time portions of the refinery were brought back online (Johnson, 2002).

In 2010 the Maule, Chile earthquake damaged the Bío Bío refinery in Concepcion, placing it out of operation for 3-4 months. When brought back online only 8 of 20 processing units were refining representing 34% of the facilities pre earthquake capacity (WSJ, 2010). The other large Chilean refinery in Concón/Aconcagua was out for 6 weeks (IEA, 2012). While no reports specifically state how fuel was supplied after the earthquake, these interruptions were likely circumvented by foreign imports. Figure 4.5 shows Chile's typical imports of different refined products. Because the country imports refined products, especially diesel (IEA, 2012), they had systems in place to receive refined products. Because of the Bay Area's large refining capacity a similar system to receive refined product may not exist.

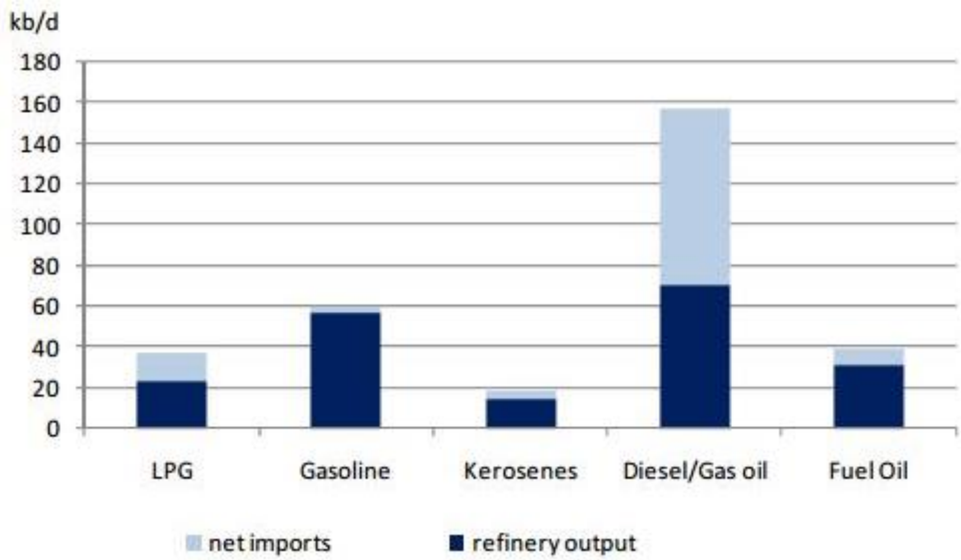


Figure 4.5 Chile's Domestic vs Imported Refined Fuels Output.

Both refineries and pipelines are at a serious risk to fail in severe ground shaking and/or liquefaction. The repair for both system components is uniquely challenging because of the hazardous material they process/transport. Underwater pipelines, or those near the shoreline may be difficult, requiring long repair times and permitting issues, but refinery repairs can take multiple months if not years. The time required to repair the Korfez and Bio Bio refineries is a uniquely long repair time, many magnitudes longer than the repair of a typical pipeline. In 2012 a five foot section of pipe in the Richmond, CA Chevron refinery failed causing a hydrocarbon leak and fire. For eight months following the fire the Richmond facility operated at 60% capacity, while repairs and checks were made to the facility. Given this understanding of past fragility and restoration and with the critical point set to 2 months, a simplified fuel system risk assessment can be performed.

4.5 System Simplification & Scenarios

The bay area fuel system has been described and mapped geographically in Section 4.3. It is common when performing risk assessments to visualize and organize the risk in fault trees. Fault trees examine the full suite of possible failures and assign a probability to each event occurring. This is an appropriate method when comprehensive assessments are possible. The reality, as has been outlined in the thesis, is that there are not values to assign to each failure, and the fault trees are too large. This thesis proposes that the problem be bounded by consequences first followed by a study of the system. This sequence allows for the omission of certain fault tree branches, resulting in a simplified system assessment. By considering the consequences of lifeline failure, the system assessments can be reduced to focus the analysis on catastrophic risk.

The traditional fault tree for the Bay Area fuel system is quite large. There are a number of ways the tree could be organized. The four primary phases of the fuel system as described in Section 4.3 are illustrated (Figure 4.6) in a comprehensive fault tree for a single scenario earthquake. A full analysis requires the consideration of multiple fault scenarios, and when a multi-hazard approach is taken the assessment of multiple hazard types is also required. Even this fault tree is slightly simplified. A more comprehensive assessment might expand this tree to consider discretized sections of pipelines too.

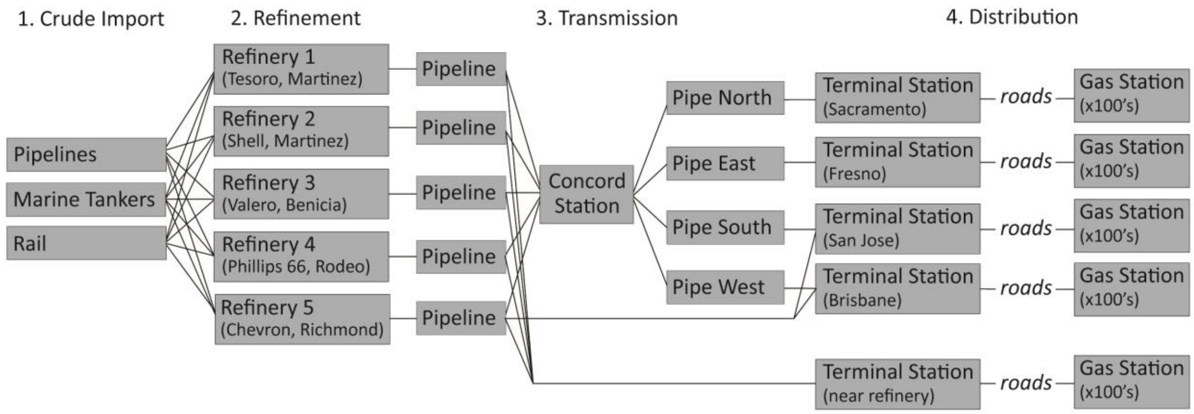


Figure 4.6 Comprehensive Fault Tree for the Bay Area Fuel System.

The fault tree in Figure 4.6 shows the need to calculate the performance of many components of the system. By simplifying the fault tree based on our critical point bound, we can simplify the tree down to two processes, the refining, and transmission of fuel. The tree is reduced to these two processes because these elements can require more than 2 months to restore operations if damaged, exceeding the critical point set in section 4.2. The fault tree in figure 4.7 ignores the risk from all crude import, pipeline, terminal facility, and gas station failures. This reduction is done by assuming that the neglected elements, if damaged, can be repaired within two months of their failure.

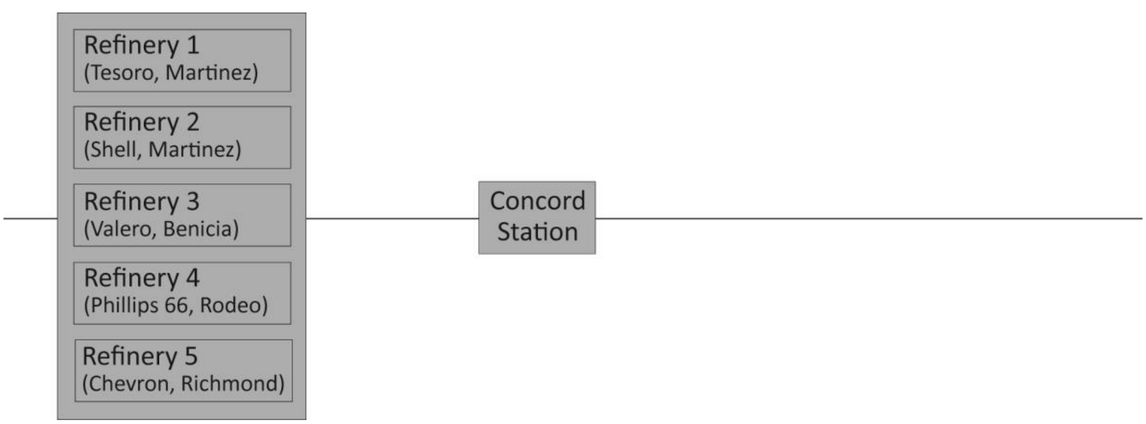


Figure 4.7: Simplified Fault Tree for the Bay Area Fuel System.

By ignoring the risk of pipeline damage the system instantly drops in complexity to the five refineries and the Concord Station. All that is left to do is determine scenarios that are most significant. Using the USGS deaggregation function for the Richmond and Martinez facilities, three events are of primary interest, earthquakes associated with the San Andreas, Hayward, and Concord Southern Green Valley faults. This can be seen in the deaggregation map (Figure 2.12 in Section 2.3.3) which shows the Hayward and Concord faults as the faults of greatest concern for the San Pablo Bay, Carquinez Strait area.

Figure 4.8 shows the fuel refineries overlaid liquefaction susceptibility and shaking scenario maps. In a San Andreas, Hayward or Concord event, portions of the Fuel production and distribution in the Bay Area is likely to be severely disrupted (see Figure 4.9). A number of similar impacts could occur in each event.

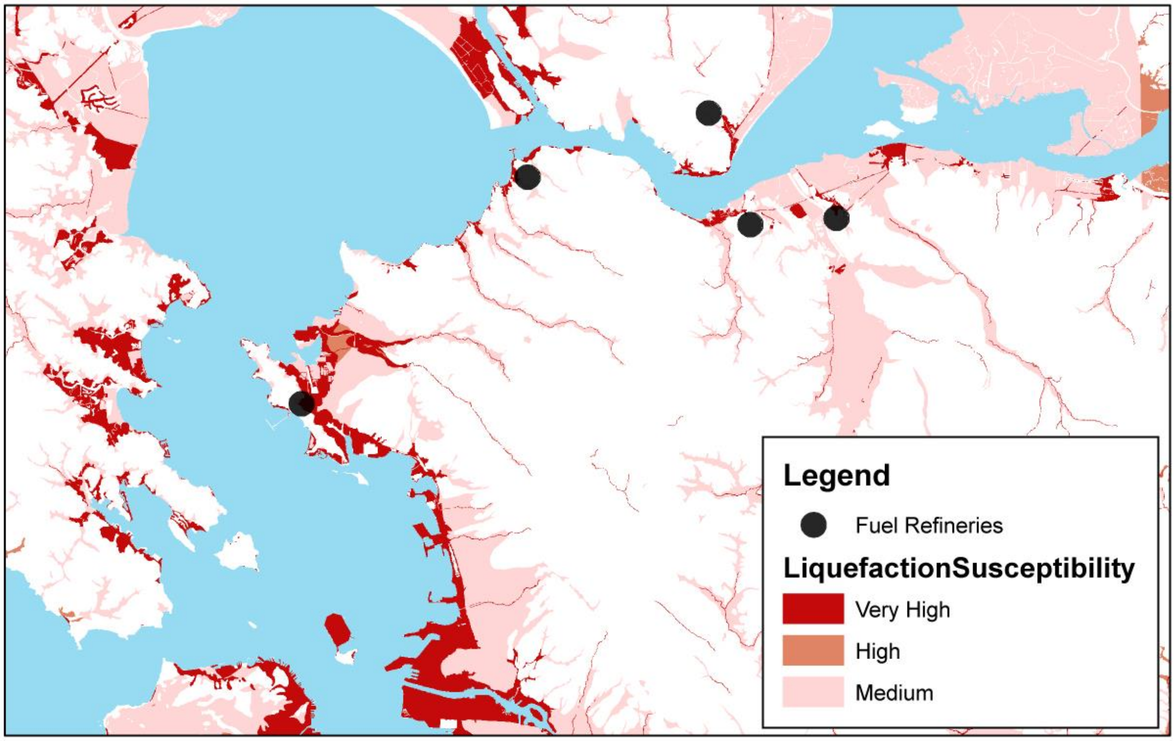
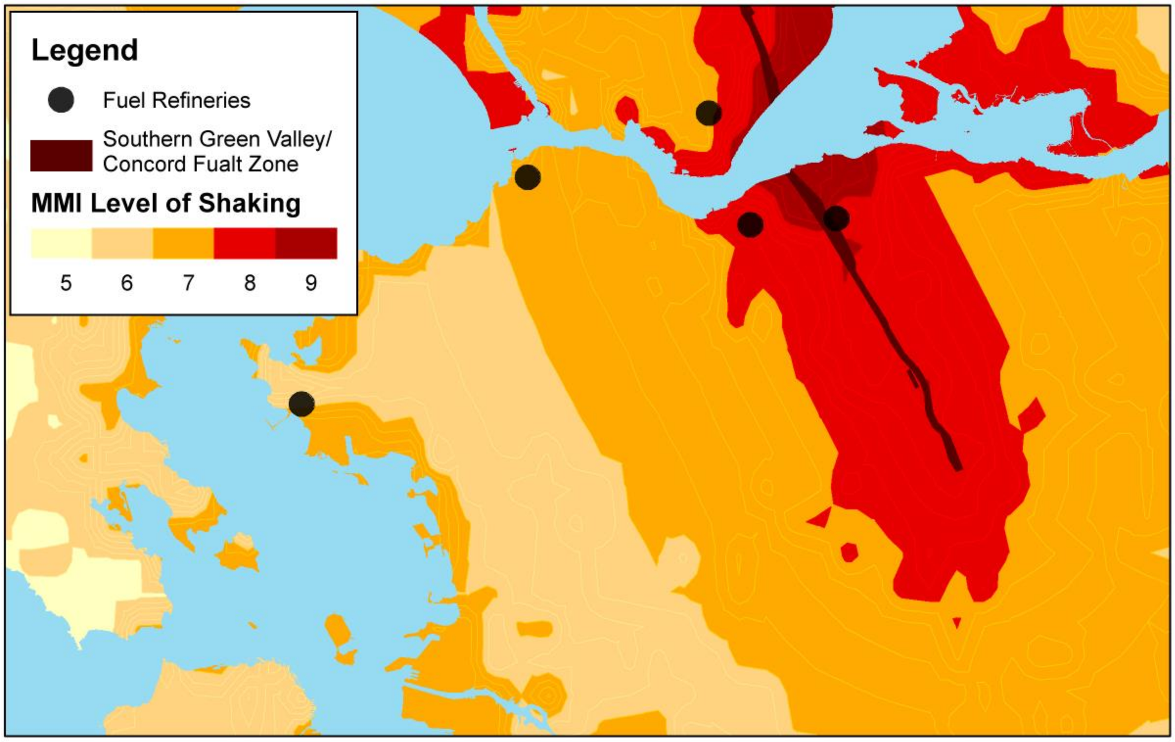
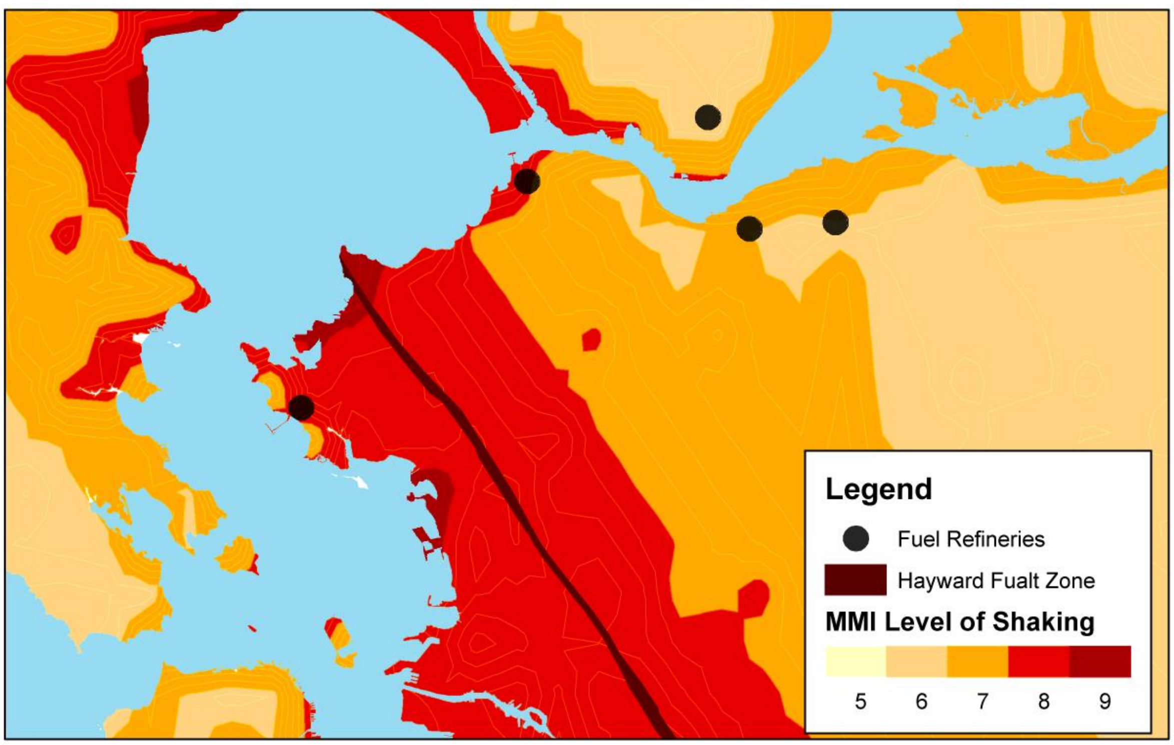


Figure 4.8: Liquefaction Susceptibility at the Five Bay Area Refineries.


Legend
Fuel Refineries
Southern Green Valley/
Concord Fualt Zone
MMI Level of Shaking
5 6 7 8 9


Legend
Fuel Refineries
Hayward Fualt Zone
MMI Level of Shaking
5 6 7 8 9

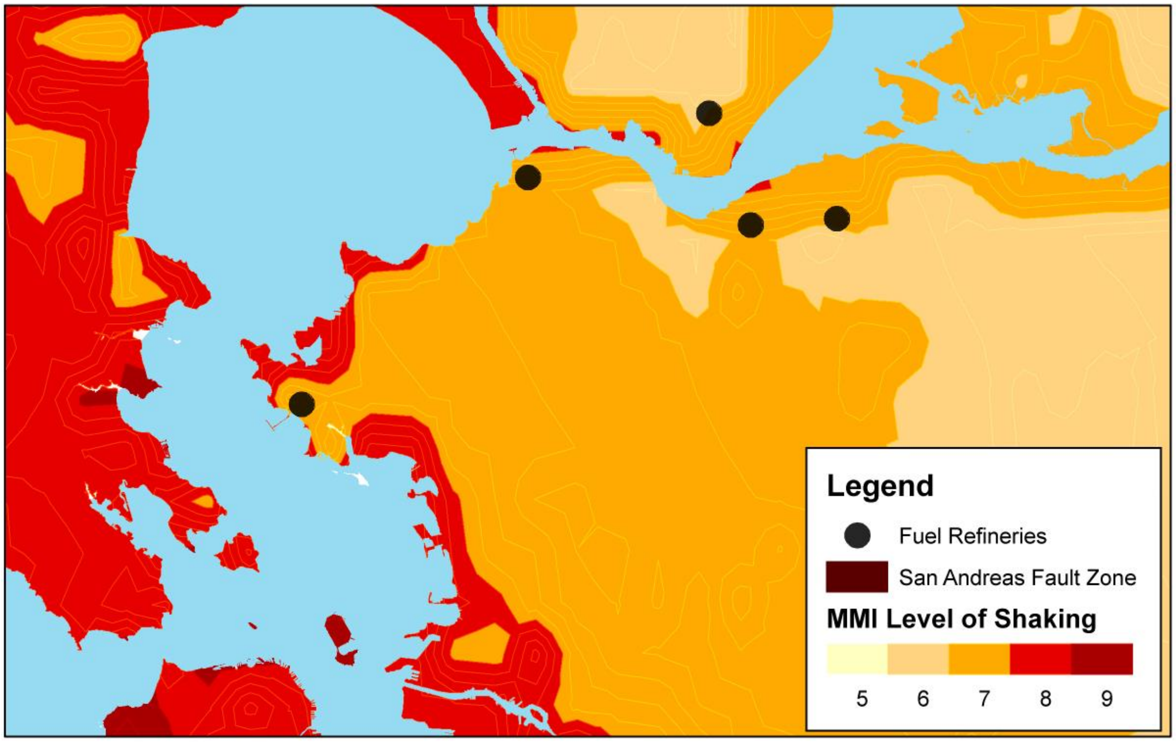


Figure 4.9 Shaking Intensity in Three Scenarios at the Five Bay Area Refineries.

Each event will cause significant shaking at all five refineries. These facilities are assumed to be sensitive and if any number of small failures occurs, the restoration of the facility could easily be on the order of months, due to the earthquake shaking alone, or due to any subsequent fires at the facilities.

By using scenario earthquakes the spatial correlation of loading is already accounted for. Because all of the refineries are generally located close together if one refinery feels strong shaking often the others do as well. This is especially true of the three refineries in the Martinez and Benicia area. Rodeo and Richmond are slightly further apart and thus tend to experience slightly different levels of shaking in all three scenario events. In addition to being in close proximity geographically they also are located in similar terrains. All the facilities are located near the bay in order to receive

crude product and subsequently are all in zones with portions of their facilities in zones susceptible to liquefaction.

In addition to their close proximity, the five refineries are all designed similarly. Although they are owned and operated by different corporations, they all refine fuel the same way and employ the same processes, and are subject to the same oversight and standards (NFPA, CPUC, OSFM). It is unknown if some of the refineries have taken steps beyond the minimum level of the regulations, but they are all required to meet minimum standards. Because of this, if the forces experienced in an earthquake are the same at two facilities, then there is likely a strong correlation between the performance of each. By considering resistance correlation implicitly when looking at the shaking maps in Figure 4.9 we can start to infer what the damage of one refinery means for the damage of others.

4.6 Monte Carlo Simulation of Bay Area Refineries

A Monte Carlo simulation was used to calculate the probability of fuel being disrupted in the region for 60 and 180 days. The simulation was run using Microsoft excel, and Appendix C has screenshots of the program. The simulation was created with the following structure which is shown in schematic form in Figure 4.10:

1. For the three scenarios introduced in Section 4.5, each refinery is assigned an MMI value based on their exposure in the scenario. These values are static.
2. Each refinery is then assigned a random number variable between 0 and 1. For each round of the Monte Carlo simulation a new random number is generated for each of the five refineries.

3. This random number is then compared against a 60 day and 180 fragility curve shown in Figure 4.11. This fragility curve was made using the limited refinery and shaking interaction seen in Chile and Kocaeli. Past “sunny-day” failures at refineries were also used to assume the fragility of these facilities, as well as the time required to restore their operation following damage. For each scenario the program compares the random variable against the point on the fragility curve for the MMI intensity experienced at that refinery in that specific event. For example, the Richmond refinery in the Hayward scenario experiences MMI 8. If the random variable is greater than 0.7, then the simulation assigns zero days of interruption at the facility. If it is less than 0.7 then it calls out 90 days of interruption. A separate column does the same interaction for the 180 day curve. With the same example, if the value is greater than 0.4 then the value is zero, if it is less than 0.4 then there is a 180 day interruption. This is done simultaneously for all five refineries. Each row of results is a unique run.
4. The summation of the refining capacity of facility is then produced to show what percent of the overall Bay Area refining capacity is impacted by each simulation run.
5. The total interrupted refining capacity for each scenario run is then compared against the critical point threshold of 50% and 33% for the 60 and 180 day points. This results in a pass or fail value.
6. At this point the results are broken up into PDF, CDF, and probability of failure results. The likelihood of each scenario event is then multiplied

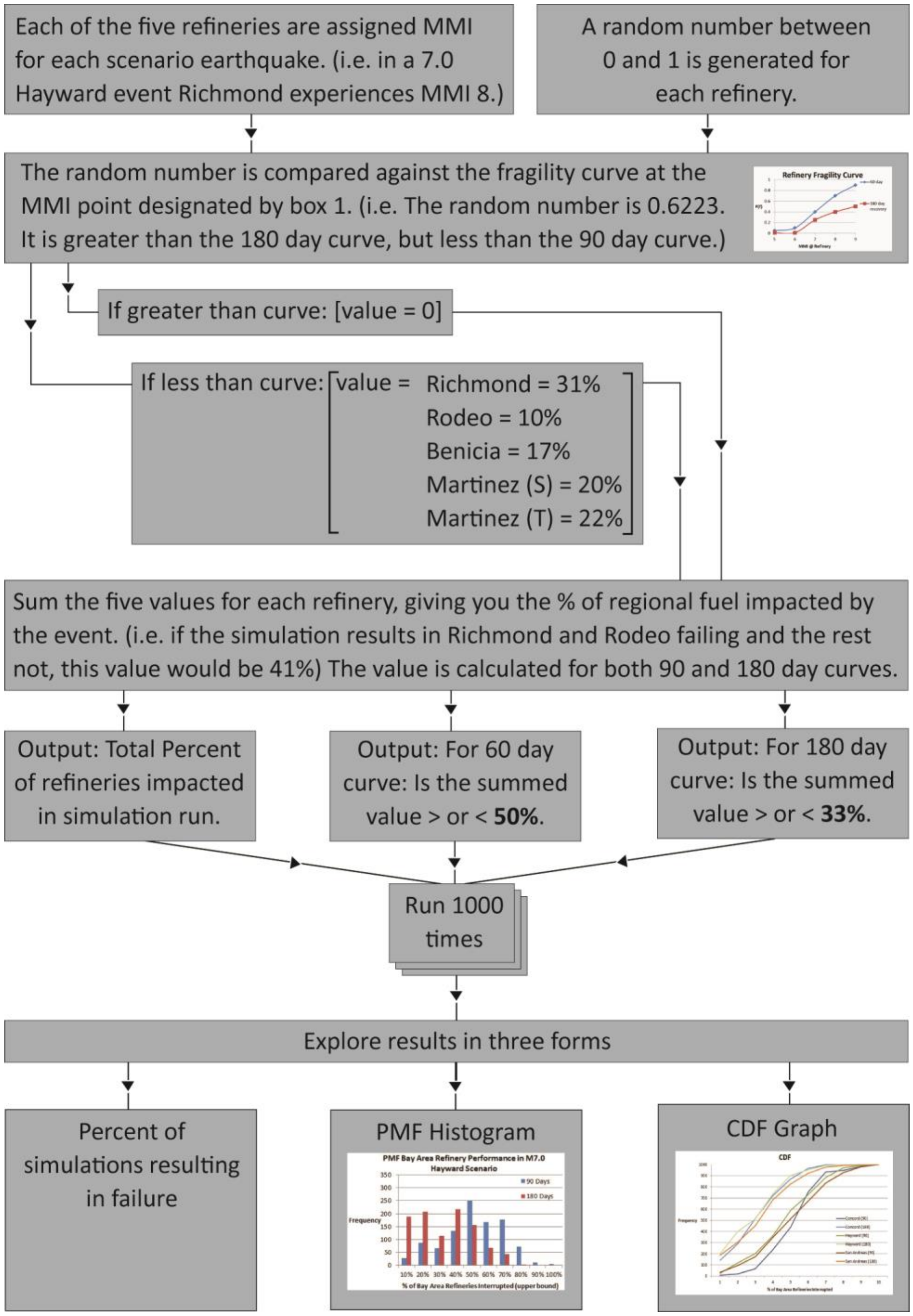


Figure 4.10: Monte Carlo Coding Schematic.

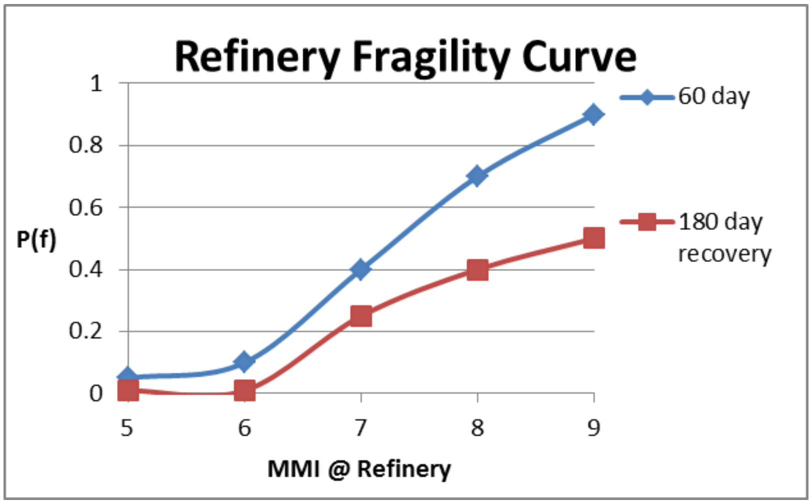


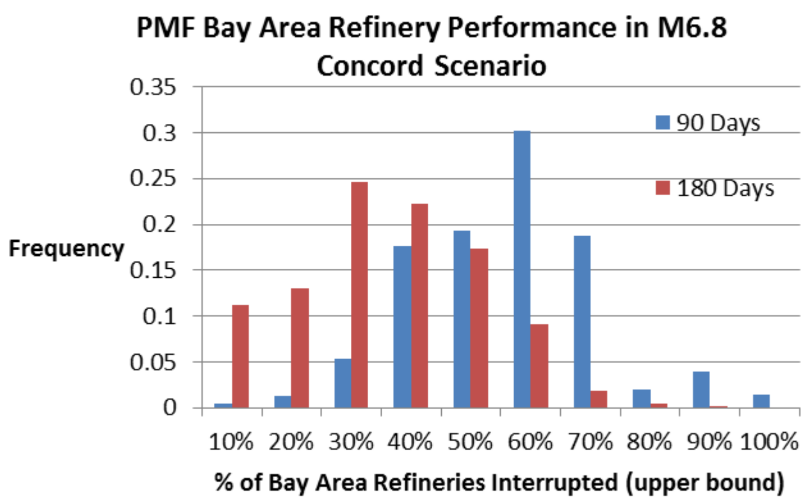
Figure 4.11: Assumed Refinery Fragility Curve.

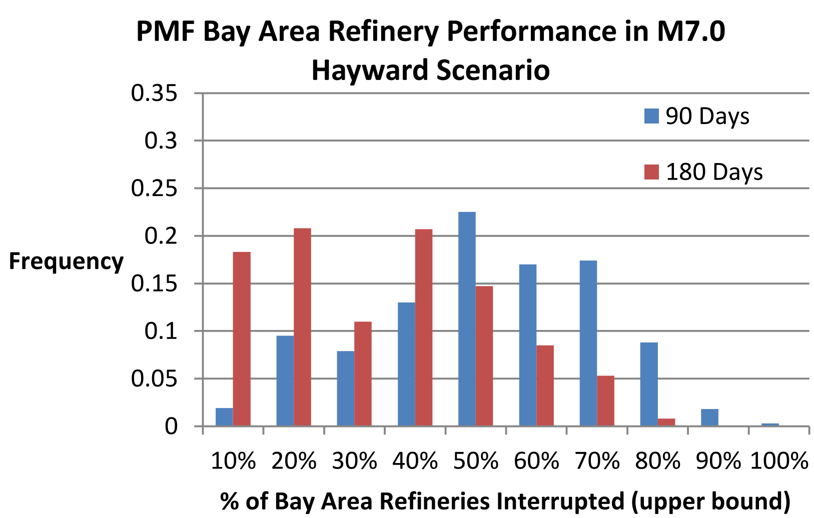
4.7 Results

Over the next 30 years there is a 17% probability that an earthquake on one of these faults of similar or greater magnitude interrupt enough of the regional refining capacity to cause catastrophic fuel outages for the Bay Area and greater Northern California. Incorporating other fault systems, and smaller magnitude events on these three faults would increase the risk of catastrophic fuel outage.

For each scenario, if it were to occur, there is a greater than 50% chance that refinery production will not be sufficient to meet the acceptance curve set. The Concord scenario had the greatest failure rate, with the refineries failing 66% of the time, followed by San Andreas, with refineries failing 60%, and in the Hayward scenario, the refineries failed in 54% of the simulation runs. However, the greatest risk for fuel production is from the Hayward scenario, because of its much greater likelihood of generating the scenario event. The San Andreas fault, while likely to produce a M6.7 or greater earthquake, remains a low likelihood to produce the M7.9 event used in this analysis.

Similarly, the Concord scenario has a much lower likelihood of occurring – compared with the Hayward fault. All in all, the refineries exhibit fairly similar results in each scenario, all falling between 54% and 66% probability of failure. Figure 4.12 shows PMF's for each scenario, and Figure 4.13 shows a CDF for each. In each chart both 90 day interruptions and 180 day interruptions are displayed.





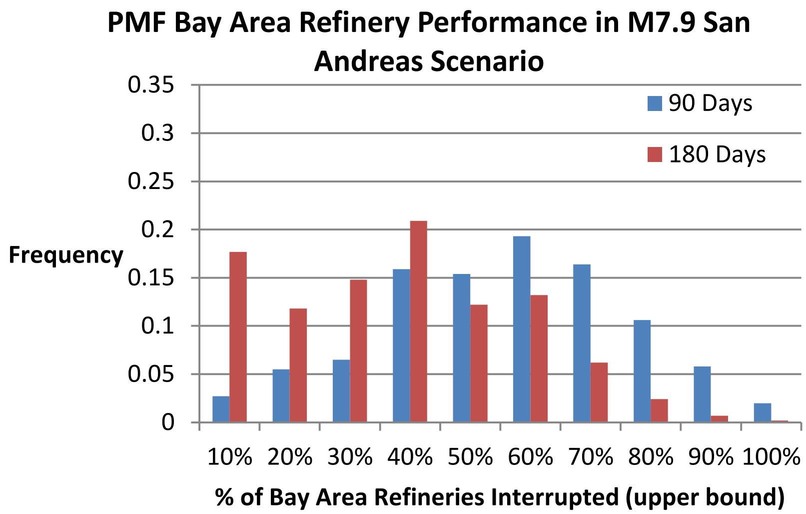


Figure 4.12: PMF for Bay Area Refinery Output in Three Scenario Earthquake Events.

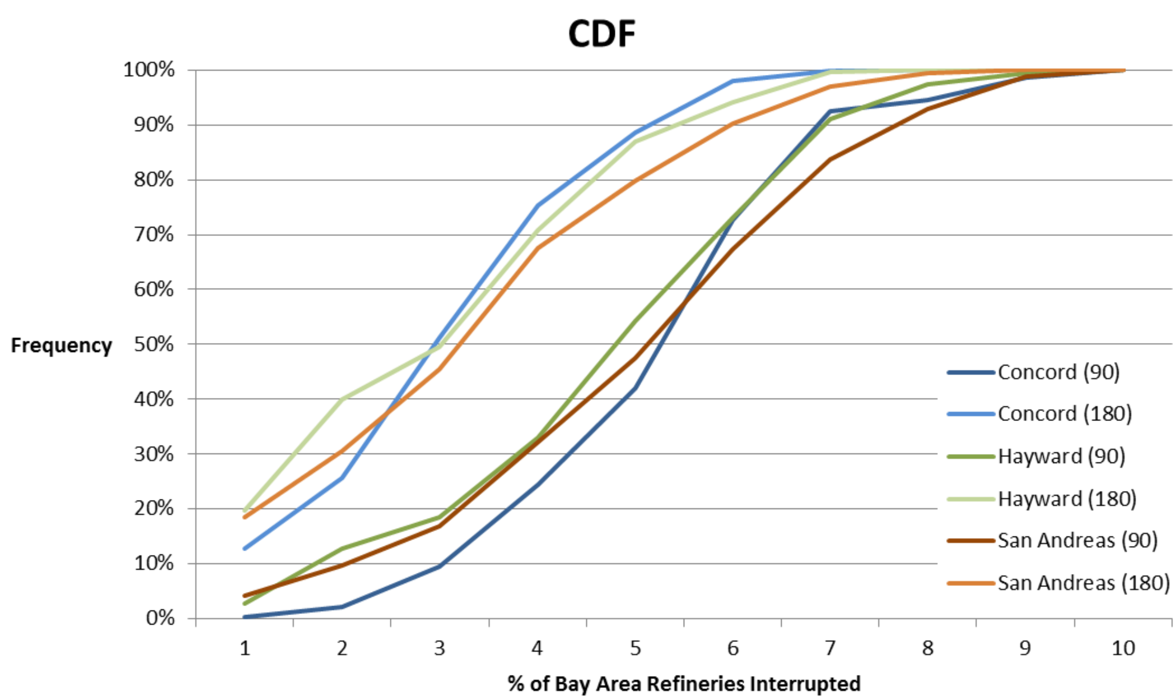


Figure 4.13: CDF for Bay Area Refinery Output in Three Scenario Earthquake Events.

Despite the unique earthquake scenarios each produces a relatively consistent picture of overall refinery performance in earthquakes. The similar results are due to the location of faults relative to the refineries, as well as the bounds set for assessment (50% impacted and 33% impacted). In San Andreas and Hayward events the Richmond and Rodeo facilities fail together, representing just over 40% of the regional refining capacity. In the Concord event, the Martinez Tesoro, Martinez Shell, and Benicia refineries experience similar shaking.

4.8 Conclusions

Without the simplified methodology there was no way to approach the risk assessment without calling on greater resources than exist for such studies. The simplified methodology first explored the relationship of different stakeholders to the fuel system, and selected the general public as the bounding stakeholder group to develop a critical point. Next, the Bay Area fuel system was mapped out, and a review of component fragility and restoration allowed for the simplification of the system down to elements that are likely to require more time to restore than is acceptable to the users of the system. System probability methods were then applied to a simplified, approachable system, providing insights that previously were unknown to the users of the system.

The result of the simplified study may be the investment of a traditional assessment with more intricate fragility curves for refineries, with the inclusion of more hazard scenarios. However, without the first initial study there is no information for decision makers to weigh investment in further study, mitigation options, or recovery strategies. The simplified methodology provides this opportunity, and opens up lifeline

system performance to the public policy world, where users can decide if systems are designed to an acceptable level of risk.

Given this analysis alone, the results could be communicated back to stakeholders and users of the system can determine if the risk acceptable. If the users decide the risk must be mitigated any number of mitigation solutions can be designed to reduce the impacts of the event. Chapter 5 explores the principles by which systems can be mitigated – all of which can be applied to the Bay Area fuel system.

5 DECISION MAKING & MITIGATION

"The quest for the missing algorithm may be like the quest for the Holy Grail: Unending and fruitless…those of us concerned with the decision sciences as they apply to problems with extreme variance must continue to develop useful means for measuring downside risk." –Daniel Alesch, 2002

Risk assessments allow for calculated, informed decisions. The previous chapters explain the difficulties of measuring risk, but decision making is an equally challenging process. Lifeline mitigation decision making is challenging because: decisions are collective, the uncertainty and the variance of risk are often large, and there are fundamentally different methods of mitigation. Sections 5.1 and 5.2 explore the difficulties of decision making when mitigation requires collective support, and when the risk profile has large variance. Section 5.3 explains fundamental properties of lifeline mitigation solutions and provides examples of past mitigation projects that embody the fundamental. The proposed simplified methodology does not suggest a single decision making scale, nor one specific mitigation strategy, rather it recognizes that decision making scales and strategies will be unique to the qualities of individual situations.

5.1 Collective Decision Making

Decisions are more difficult when multiple stakeholders are involved. When deciding what level of water reliability is necessary, the more people involved, the more difficult the decision becomes. Lifeline systems are largely collective (both publicly and privately owned), with all stakeholders in a geographic region relying on the same system. This creates a conflict between individuals who want to invest in a higher standard of infrastructure performance, and those who are content with the current risk

and would be burdened by investing further. As discussed in Section 3.1 some organizations may be more reliant on lifelines and may experience greater losses. While the outage length for two entities may be similar, the consequences will be unique and different. The difference between consequences makes decision making difficult. In addition to this difference in consequence, there are other qualifying factors that influence individual rational risk decisions: institutional size, customer traits, and reliance on local resources.

Individual decision making will depend greatly on the size and diversity of organizational portfolios. Much like parallel system structure, having operations spread across multiple regions whose risk and function is not connected, allows for the failure of one region to not cause irrecoverable losses to the organization. Conversely, a small business owner with one facility is unable to take the same approach. Large corporations or even “the federal government should be treated as risk neutral because of [their] high degree of risk diversification. Whereas the federal government can be risk-neutral on virtually all of its own projects, the same is not true of other governmental and private sector entities….state and local government lifeline entities as well as private sector lifeline entities cannot be so sanguine about potential risks,” (Alesch, Nagy & Taylor, 2002) and should be risk averse to prevent catastrophe. The difference in consequence as well as difference between risk neutral and risk adverse lead to a range in scale of mitigation solutions.

Depending on the ability to reach consensus, lifeline mitigation can occur at three levels: micro, meso, and macro scales. Micro solutions are completed by individuals or single organizations. Meso solutions bring together portions of a population, typically an

economic sector or cooperative group. Macro solutions bring together all individuals and markets (Rose et al. 2007). Figure 5.1 shows these three scales and examples of each.

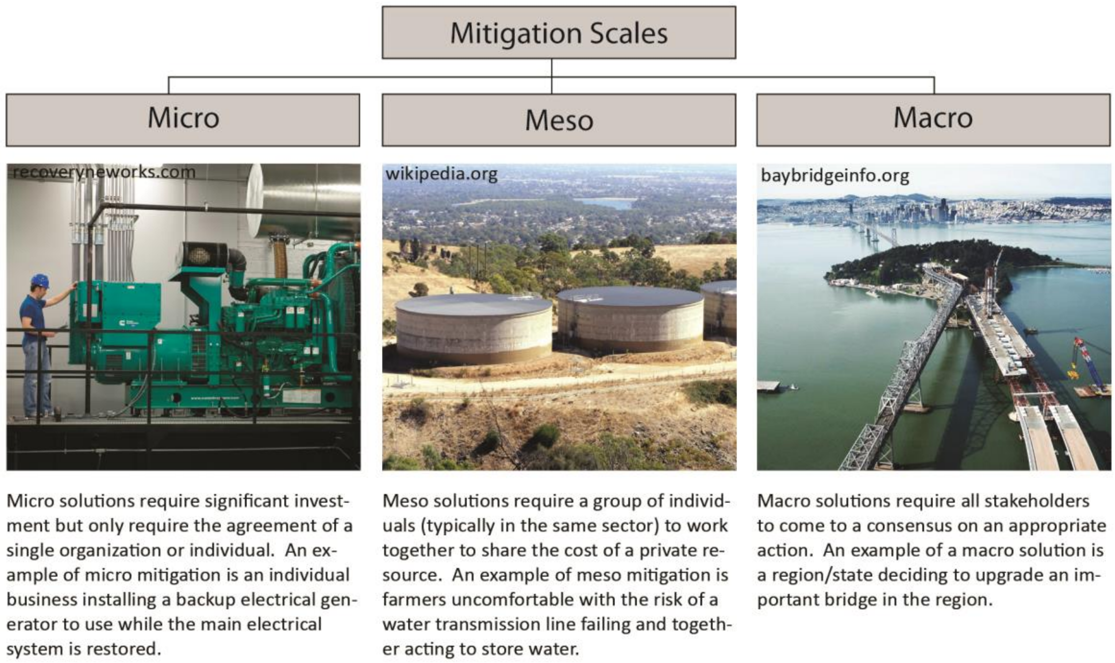


Figure 5.1: Scales of Mitigation: Micro, Meso, and Macro.

Stakeholders who desire lifeline performance greater than the public system must invest heavily in a private solution (i.e. electrical generator, water storage, waste storage, satellite communication) or convince the public to invest in more robust infrastructure systems. In most cases individual solutions are not feasible, except for sensitive businesses and institutions such as hospitals, emergency operation centers, or a corporate headquarters. In California hospitals are required by the state to have gas and water storage as well as electrical generators to ensure their ability to provide public health services following an earthquake (HSSA, 1983). The International and California building codes have reflected this legislation in their respective 2006 and 2007 codes

requiring generators, fuel storage, HVAC systems to all be tested on shake tables before they are installed in a building (Tobolski, 2011). Hospitals are not the only facilities that require lifelines to remain operational, many businesses require lifelines to maintain economic function. Regardless of the business, all are reliant on infrastructure with the majority of businesses unable to function minutes into an outage. Like hospitals some organizations have prepared with micro solutions as well.

While some organizations have chosen to mitigate and prepare with micro solutions, regional economic resilience is dependent on macro mitigation projects; "Mitigation and preparedness measures undertaken at the level of the individual business must be balanced by the macro-level approaches that focus on maintaining the functionality of communities and local economies," (Tierney & Nigg, 1995). Micro solutions are limited and only support single entities. If an institution chooses to invest in micro solutions that results in the function of their facility, they are often still reliant on functioning suppliers, customers, and employees with functional homes to maintain business as usual. Even for the most risk-averse individuals micro solutions simply can't mitigate their risk because of cost or because some lifeline services simply cannot be mitigated by individuals. Many systems are inherently macro and require communal agreement and investment.

5.2 Uncertainty & Variance in Decision Making

Even in the most well studied regions of the world, the public is often inactive in addressing earthquake risk because events are infrequent and the uncertainty is great. Probabilistic risk assessments provide valuable information for rational decision makers,

but even the most complete assessments can result in limited mitigation action. With limited success in mitigation without a triggering event, it is important to improve the communication of both uncertainty and risk in an effort to achieve proactive mitigation before earthquakes occur.

The uncertainty in the likelihood of earthquakes and the uncertainty in the performance of a system both before and after mitigation are barriers to investment. Mitigation can be a tough sell with other more concrete demands competing for funding. Because of uncertainty, mitigation occurs more often following an event when the public is witness to the hazard, the system deficiencies, and the losses that follow. In the aftermath of events, the consequences are real and specific. Risk assessments attempt to reveal deficiencies prior to an event but uncertainty is an unavoidable reality of predicting system performance. Reactive improvements following earthquakes are beneficial, but proactive mitigation is ideal.

Despite large improvements in the geo-sciences in the past decades, earthquakes will remain events with great uncertainty. The uncertainty can be broken into the where, when, and how severe an earthquake will be. In well studied regions of the world there is less uncertainty in the where component; although Christchurch (2011) and Northridge (1994) were both on previously unmapped faults. When an earthquake will occur has the greatest uncertainty, and has not been successfully forecast on a human time frame.

Earthquakes occur over a geologic time frame and while “It would be useful to have access to reliable probabilities concerning the frequency, magnitude, and proximity of a natural disaster in relation to a specified location or set of locations…we are so far unable to provide that information reliable within the time frame relevant to most

decision-makers. That is, it may be possible to make reliable predictions plus or minus 100 years, but not plus or minus 10 years," (Alesch et al. 2002). Others might go further and suggest 100 year predictions may be out of reach and really 1,000 or even 10,000 years are required for an accurate resolution. The Parkfield earthquake is a good example of the level of uncertainty in predicting events. In an effort to study a number of seismological characteristics the earthquake community instrumented a section of the San Andreas in Parkfield, CA which over the previous century consistently had M6.0 earthquakes dating back to 1857, one of which was a precursor to the Ft. Tejon earthquake. All six earthquakes ruptured the same section of fault and were all similar in size. If the pattern in time between ruptures were consistent, the next Parkfield earthquake should have occurred before 1993 (USGS, 2012b). 11 years later in 2004 a M6.0 Parkfield earthquake occurred. Presently when earthquakes occur cannot be predicted at a human timescale.

The severity of the earthquake is also highly variable. While Parkfield was close to the expected magnitude, outlier events like the 2011 Tohoku, Japan event occur. The length and type of fault offer bounds for potential magnitudes, and paleo-seismic fault trenches can also help determine the size of past events, but even with the most current science, some argue that the severities of earthquakes extend beyond any feasible level of design. "All risk from earthquake damage cannot be eliminated. No matter how much money is spent in strengthening structures, some earthquake could occur that would damage the structure even to the point of requiring replacement. Strategies must be developed to manage what risk remains in ways acceptable to the owner," (Wittkop &

Jensen, 2002). It is not simply the uncertainty of seismic events, but also the wide range of consequences when they do occur that makes decision making difficult.

The variety of potential consequences makes decisions difficult, and makes insurance an attractive option for most. In insurance it is common practice to annualize earthquake losses for clients and eliminate the bi-modal representation of the probability. For stakeholders where insurance is not financially feasible annualization is less successful. For a single business the majority of years will yield zero losses due to earthquakes. However given the earthquake occurs there is the potential for a range of damage states and consequences which are capped by catastrophe/bankruptcy/death. Uninsured stakeholders must understand that the loss potentials given an earthquake will occur at once and not over time. Decisions may be made more simply when catastrophic risk is specifically addressed.

> *"Because the events are so rare, and sometimes so devastating, the variance in annual costs can be extreme…when the variance is large and when the potential for ruin exists, the decision making becomes a lot more difficult…In the case of hazard mitigation, the prudent decision-maker will attempt to reduce downside risks by defining what constitutes ruin for that firm, reducing variance in possible outcomes to be above that level, and why then seeking a mitigation investment that achieves the desired level of safety at the lowest possible cost, subject to the demands of other competing uses for the resources," (Alesch et al. 2002).*

For a sustainable business continuity model, understanding the outage length that results in ruin is an important variable to know. This variable is c, the critical point in EQ 1.3.

Not all risk needs to be mitigated, only catastrophic risk. Stakeholders are then left to determine appropriate action to prevent ruin, in the process making themselves resilient.

5.3 Fundamentals of Mitigation Strategies

There are three primary ways to mitigate lifeline systems directly, lifeline performance systems can be made more redundant, robust, or repairable. Each fundamental will be more or less appropriate than the others given factors of unique situations. The system, the stakeholders, and the hazard will all influence which fundamental strategy may be most successful.

5.3.1 Redundancy

Redundancy is achieved by parallel system structure and/or multi-modal delivery. Parallel structures have multiple components within an individual system performing the same task. Multi-modal delivery has different systems performing the same function. In both, a truly redundant system will have small correlations, or better yet negative correlations (if one link fails it is likely the other did not). For high level transmission systems parallel segments can be placed tens of miles apart, decreasing the likelihood both experience the same event. At the local level this is difficult because an entire city can simultaneously experience high hazards. Parallel infrastructure components at the local level may have correlated performance because the hazard forces are similar across the whole city. When dealing with infrastructure systems at a local level multi-modal systems offer a means to provide redundancy. In Loma Prieta the Bay Bridge failure

highlighted the need to make key transportation corridors multi-modal. Mitigation measures like the replacement of Bay Bridge are needed, but investing in multi-modal systems along key transportation corridors is equally important. A multi-modal system can "withstand shocks to parts without catastrophic damage to the whole," (Schiff, 1990). More generally, where single corridors exist having multiple modes (personal vehicles, trains, ferries, cycling, pedestrian) can be a method of diversifying series system corridors, making them more redundant.

Using the fundamental of redundancy, the City of Berkeley in 2000 developed an innovative aboveground water supply system (BAWSS), improving their firefighting water system by means of another mode. The system has vehicles that lay large diameter flexible hose reaching from a water source (the bay, a reservoir, or a working water main) to most portions of the city (Orth, 2011), Figure 5.2. Unlike San Francisco's AWSS, BAWSS is not directly vulnerable to liquefaction. AWSS is a parallel network of pipes independent of the municipal water system, but it is still reliant on pipes and underground infrastructure at risk of liquefaction as was the case in Loma Prieta (Section 2.1.1). BAWSS isn't without its own weaknesses. Roads must be passable enough to deploy the system from a water source to the fire. Both AWSS and BAWSS are some of the best existing examples of redundancy, AWSS with a robust network of parallel piping and cisterns, and BAWSS with a different mode of water supply. Firefighters in both cities are more prepared than most to have water to fight fires following earthquakes. But fire suppression requires more than high pressure water, communication and transportation are also necessary.

Figure 5.2: Demonstration of BAWSS Deployment (Orth, 2011).

Most fire departments have invested in their own independent and redundant communication system of radios or satellite phones, but transportation networks are a challenge. Fire boats and aircraft would offer an uncorrelated redundant solution to trucks reliant on roadways but are largely unrealistic options. Similarly, a separate system of roads for first responders is not feasible. Some innovative micro solutions may drastically improve the ability of first responders to navigate a damaged transportation network. ShakeCast, a Caltrans program, is used to help improve response times (Turner, 2011). The program provides first responders with an expected bridge damage inventory minutes after an earthquake allowing crews to bypass potentially damaged bridges. Continued micro strategies should be developed for first responders, but when redundant systems aren't feasible, increasing the robustness and reparability of macro lifelines is necessary.

5.3.2 Robustness

Robustness is achieved by making elements more resistant to failure. This can be accomplished by increasing a components strength or flexibility. The advantage of making elements more robust is that their probability of failure decreases, which then has a direct effect on the risk. Transbay transportation in the Bay Area has previously been described as a redundant system that performed as such in the Loma Prieta earthquake. The consequences of the Bay Bridge closure for 30 days were hedged by BART, ferries, and other bridges. Nearly 25 years after the earthquake the region opened a more robust Bay Bridge that greatly increased the reliability of vehicular transportation across the bay following a future earthquake. Despite redundancy between the BART, Ferry, and bridge systems, the potential for much larger and more centrally located earthquakes in the bay area could damage the bridges, tunnels, and ports that were undamaged in Loma Prieta. By making the Bay Bridge robust the reliability of transportation across the bay increased significantly. A robust solution was appropriate for the Bay Bridge because other bay crossings will likely experience similar earthquake forces in future events, and speedy repair of such a large structure may be infeasible. Other situation may call for a different solution.

5.3.3 Repairability

When consequences are not immediately catastrophic due to interruption in lifeline service, a repairable system may be an appropriate mitigation strategy. Lifeline components can be designed to limit outage time by accepting that failure of components is likely, and designing them in a way that allows quick repair or replacement. When the

length of lifeline outage is the governing variable, then it may be allowable for there to be extensive failures if those failures can be readily replaced following the event. Understanding what the critical point of lifeline outage is for stakeholders can provide information on repairable solutions that can provide temporary fixes to return systems to operational performance. Water providers have largely embraced this philosophy when designing pipe systems that cross over faults. Designing a pipe to perform with multi-meter fault rupture may not be cost permissive, and may not provide a design that provides a low enough probability of failure. Instead recognizing locations where fault rupture will occur and placing shut off valves and bypass connectors is a solution that offers water transmission soon after an event.

5.3.4 Discussion

Ideally systems could all be redundant, robust, and repairable. One such system incorporates all three fundamentals into a single system, Figure 5.3. In 1994 more than 90% of East Bay Municipal Utilities District's customers supported a $189 million Seismic Improvement Program to strengthen the water system against major earthquakes (ABAG, 1998). The community reliant on EBMUD water experienced brief outages in the 1989 Loma Prieta earthquake, and were exposed to the 1991 Oakland Hills Fire that killed 29 and burned over 3,000 homes (Eidinger, 2004). In January of 1994 Northridge struck Southern California. The combination of Loma Prieta, the Oakland Hills Fire, Northridge, and an extensive education outreach of the potential impacts of a Hayward Fault earthquake, garnered mass support for the EBMUD water system improvements. Similarly, San Francisco passed its own bond measures to bolster their water systems.

Residents were receptive to rate increases to improve the seismic performance of their water systems.

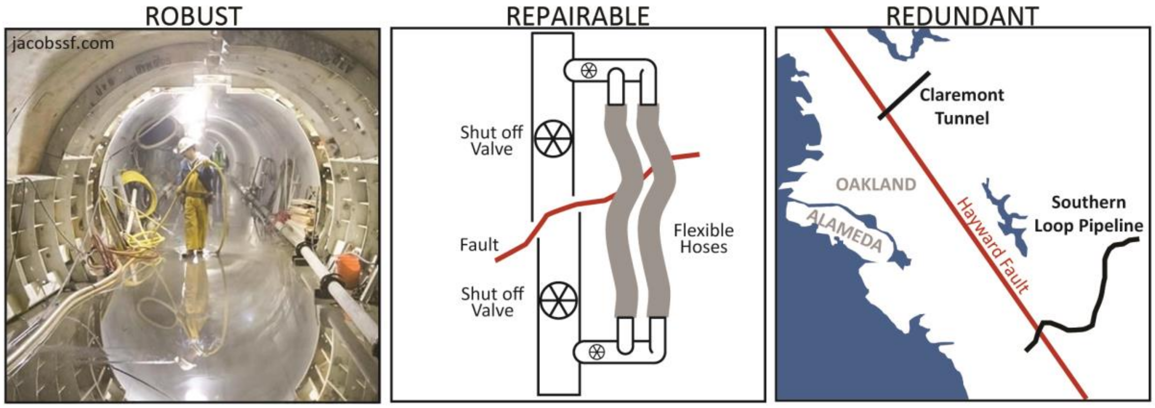


Figure 5.3: EBMUD's use of Robust, Repairable, and Redundant Lifeline Mitigation Fundamentals.

EBMUD completed two main projects to improve their system reliability. The first improved robustness. The Claremont Tunnel underwent a seismic strengthening where it crosses the Hayward Fault underground. The construction cost of the project was $38 million, but the pipeline is expected to function following a Hayward earthquake despite a fault displacement as great as 2.5m. While this improvement alone greatly increased the probability of water supply, EBMUD also constructed a parallel water transmission bypass. The southern loop pipeline was built to add redundancy to the water transmission system (EBMUD, 2012). The additional water transmission line also crosses the Hayward fault, but at a different location, where the fault rupture is expected to be less. They would be entirely independent of fault rupture damage in the event that only the northern or southern portions of the fault slip. The additional line and different location spatially, greatly improve the likelihood of at least one of the transmission lines functioning following a future Hayward rupture. The southern loop pipeline and other

smaller diameter pipes in the EBMUD system that cross the Hayward Fault have emergency bypass valves where water can bypass any damage caused by fault rupture with large diameter hose (EBMUD, 2005). EBMUD has invested in measures that greatly improve their ability to provide water following an earthquake. While they recognize there will be thousands of failures in the pipeline system they have addressed the highest hierarchy of their system along sections that otherwise could require a long time to repair. These examples were largely spurred by past lifeline failures. If risk assessments can be completed and communicated properly they may be the tool to achieve mitigation without a catalyzing disaster event.

5.4 Summary

By using the simplified methodology stakeholders are provided with an assessment that specifically studies catastrophic risk. This directly addresses the issue of variance, focusing decision making on reducing the catastrophic risk, and focusing the stakeholder to consider the risk that results in ruin. Because the assessment focuses on this portion of risk the mitigation solutions that arise as a result will directly improve resilience.

When the risk assessment becomes a resource for decision making the scale and fundamentals of mitigation should be communicated. There is no single mitigation scale nor strategy that is best. The mitigation scale and strategy chosen should be dictated by the unique conditions of individual systems and stakeholders. Lifeline mitigation can be undertaken at three different scales, micro, meso, and macro, each requiring a different level of consensus. When mitigation strategies are explored there are three fundamentals

that can each provide the desired system operability. Systems can be made more robust, repairable or redundant. This chapter largely covers mitigation fundamentals completed on the macro system but as described in Chapter 3 if the results are communicated to end-users, it may improve their ability to implement micro strategies which decrease their reliance on a fragile system. The fundamental solutions in this chapter describe how to improve the system performance, but when resilience is the end goal, increasing the end-users acceptable outage before the critical point also improves overall resilience.

6 CONCLUSION

"It's a dynamic field. Every time I think I've got it I realize I'm just an advanced beginner" – Steven Jordan

Lifelines pose a complex problem for assessment. The primary goal of this thesis is to steer the thinking about lifelines to encompass not just the vulnerability of lifeline systems, but the consequence of failure. From a theoretical perspective understanding the entire system is a desirable goal, but often an infeasible one. By understanding consequence first, systems can be simplified to the components that will govern catastrophic outages. The simplified methodology does not result in a comprehensive risk assessment, rather it provides an abbreviated risk profile of catastrophic risk; risk that constitutes ruin. By providing an assessment of only catastrophic lifeline risk, the risk of greatest importance is measured, while smaller recoverable risk remains unknown. Many of the same probabilistic issues remain, but by simplifying the process, abbreviated lifelines assessments are more feasible providing stakeholders with information to make decisions about catastrophic risk in an environment that currently is largely unknown.

For these reasons the proposed simplified assessment provides a good model for a variety of stakeholders to study their lifeline risk. States and regions that invest in lifeline assessments can provide a valuable resource for other stakeholders to build from. If findings are communicated to businesses and residents, and the risk is unacceptable they can choose to invest in appropriate lifeline mitigation; by investing in a personal micro solution, working with partners on a meso solution, or generating the political support necessary to fund municipal infrastructure improvements, or oversight to ensure private lifeline systems are reliable.

6.1 Potential Pitfalls of the Method

The deeper lifelines are explored the more complex they can become. Generating simplified assessments can provide valuable baseline knowledge for a wide range of stakeholders. Because the methodology simplifies assessment it could be missing sources of catastrophic risk. By removing elements from an assessment there is a chance a significant component is omitted. Take for example the fuel study provided. In the study the pipelines were ignored from the assessment with the assumption that pipelines can be repaired more rapidly than other key nodes. If pipelines were more sensitive than thought and multiple failures occurred in the series pipeline system it could arguably take longer to repair an entire pipeline than restore failed refineries or pumping nodes. The same argument applies to any simplification. This concern can be addressed by clearly communicating results, stating assumptions and adding a disclaimer that the assessment is simplified.

The fuel assessment paints a granular picture of the potential for catastrophic fuel disruption. Because the fuel sector is so critical to the region, building out the study could smooth the picture making it a valuable resource for the region to address resilience. While the methodology may not capture the whole risk, it allows stakeholders insight into possible magnitudes of risk, which may then produce the will required for further study, and for access to greater amounts of data needed for a more complete assessment.

6.2 Future Research

In the lifelines field there are still a number of research avenues that would greatly improve this methodology. Any improvements in lifeline data collection or correlation relationships would prove very fruitful for both a traditional probabilistic lifeline assessments as well as the simplified assessment described in this thesis. This thesis can also be greatly improved by greater study of the consequences and the engagement of lifeline operators.

6.2.1 Technical Study

Understanding the relationship between hazards would be very beneficial in understanding the hazard forces comprehensively. When using scenarios as is suggested in this study for lifeline assessments, existing liquefaction susceptibility maps are not currently helpful. While developing liquefaction susceptibility maps at a detailed level may require years of research and subsequent testing in the location of interest, developing basic red-yellow-green liquefaction scenario maps with existing ground shaking and soil liquefaction maps should be feasible. This information would be beneficial for system studies where ground shaking may be a concern along one system segment and ground liquefaction may be a concern along a parallel segment (i.e. The Highway 101 and 280 corridor described in section 3.4.3.1).

6.2.2 Consequences

If the simplified methodology proves helpful there is a much greater need to measure and track consequences following disasters. The earthquake and hazards field has prioritized reconnaissance efforts on documenting failures, and less time on studying the consequence of the failure. In the case studies of the fuel refinery failures in Kocaeli and Chile there were multiple reports describing the structural damage, but nearly nothing discussing what the impact of the failure was and what measures were taken to lessen the impact. Knowing the fuel demands in the days, weeks and months after the earthquake and studying the short term fixes would provide invaluable knowledge into what types of impacts might be expected in future events. This is something that needs a longitudinal study.

In addition to the study of lifeline system recovery, it is important to understand the interaction of stakeholders with lifeline services. There has not been an update of the mid 90's Tierney study of the reliance of business on lifeline sectors. In the past twenty years the internet, businesses models, and other advances have likely drastically changed the reliance on lifelines following earthquakes; making some systems more critical and others less. Continually understanding the relationships of regions to their infrastructure will provide insight into what types of measures are most necessary. Additionally, studying the impact of various outage intersections, may provide insight into which systems should be balanced in their mitigation approach (i.e. study impact of having both water and wastewater rather than just one).

Lastly, the study of consequence and the generation of mitigation strategies must expand beyond simply the time of outage and include the quality, quantity, and distance

to infrastructure systems. This more complete understanding of consequence can drastically change what portions of systems should be studied and can also be used to generate better response and emergency plans that address each of these scales. This adds a layer of complexity but the value achieved could generate unique mitigation and recovery strategies.

6.2.3 Policy & Collaboration

The first two topics of study can be carried out by researchers in the earthquake engineering and emergency management fields. Engaging with lifeline operators is a critical step in retrieving data to run assessments, and also having a partner that will be open to macro level solutions. Without willing partners, users of the lifeline systems when handed assessment results will be left to mitigate at micro and meso scales, sometimes infeasible options. Groups like the City and County of San Francisco's Lifelines Council are beginning a long process of bringing lifeline operators together to share information with stakeholders (City of San Francisco), and possibly more importantly with one another. This Council while young, could act as a trailblazer for regional or state lifeline councils that can tackle problems at a higher level, lending themselves to completing simplified assessments of transmission systems.

The collective effort to mitigate lifelines can be a difficult process of collaboration or political intervention. In the past studied systems in high hazard areas have generated political support to fund large improvement efforts. Water and transportation systems in California have completed extensive seismic retrofit and seismic reliability programs resulting in more resilient systems. Private systems have

improved their performance through similar programs but it remains to be seen if their improvements have been as extensive. If individual systems continue to fail disproportionately to others, decreasing the resilience of all stakeholders within the region, policy action may be necessary to improve reliability. Study of the efficacy of past methods for both private and public systems may provide guidance in necessary steps following future failures.

6.3 Final Thoughts & This Work in the Real World

We can't get to resilience without considering the risk to our lifeline systems. Over time our social and economic drivers have become increasingly dependent on aged systems, fragile to natural hazard forces. The realities of lifeline system management have made it difficult or impossible to apply theoretical risk models to understand our risk. The proposed simplified methodology acknowledges these realities and suggests a first step that can be taken to understand catastrophic risk for the users of infrastructure systems. The results don't provide users with a comprehensive risk profile, but rather a granular understanding of the risk that constitutes ruin for the stakeholder.

For more content on this topic, there are three documents that were written in conjunction with this research. For the first time in 2013, the *California State Hazard Mitigation Plan* included an annex dedicated to lifeline risk assessments (see Appendix A) a first step in addressing lifeline risk. It is a short annex and is framed to help local jurisdictions address their lifeline risk in Local Hazard Mitigation Planning. Appendix B is an assessment of many Bay Area infrastructure systems. Elements of the methodology were used in the *Cascading Failures* report, which includes portions of the Bay Area fuel

system analysis highlighted in this research. Lastly, the research was also included in the *California Adaptation Planning Guide* which highlights how communities can build adaptation into their planning efforts, one element of which includes the planning of existing and future infrastructure systems. The approach taken in this thesis was bounded by earthquake hazards, but the methodology and many of its nuances can be applied to all current and future natural hazards.

BIBLIOGRAPHY

American Red Cross. (2011). Report of the 2010 Chilean Earthquake and Tsunami Response. U.S. Department of the Interior, U.S. Geological Survey. Pincipal Investigators: Hinrichs, R., Jones, L., Stanely, E., Kleiner, M. Open-File Report 2011-1053, Version 1.1 Retrieved From: http://pubs.usgs.gov/of/2011/1053/of2011-1053.pdf

AAPA. (2012). North America Container Traffic 2011 Port Ranking by TEUs. Advisory. April 30, 2012. Retrieved From: http://aapa.files.cms-plus.com/PDFs/NORTH%20AMERICA%20PORT%20CONTAINER%20TRAFFIC%20RANKING%202011_1361895265064_1.pdf

ABAG. (2014). Cascading Failures: Earthquake Threats to Transportation and Utilities. Association of Bay Area Governments. December, 2014

ABAG. (2013a). Sub-Regional Earthquake Hazards and Earthquake Mapping Update. Association of Bay Area Governments. November 20, 2013.

ABAG. (2013b). Policy Agenda for Recovery. Regional Resilience Initiative. March 2013. Retrieved from: http://quake.abag.ca.gov/wp-content/documents/resilience/Regional%20Resilience%20Initiative%20Policy%20Plan_March%202013.pdf

ABAG. (1998). How Have ABAG's Ground Shaking Intensity Maps Been Used or Not Used? East Bay Municipal Utility District – Seismic Improvement Program. Seismic Improvement Program Staff. Retrieved From: http://www.abag.ca.gov/bayarea/eqmaps/doc/1998simaps.html

American Community Survey. (2012). Selected Economic Characteristics 2012 American Community Survey 1-Year Estimates. Geography Counties: Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, Sonoma Counties.

Ang, A., Tang, W. (2007) Probability Concepts In Engineering: Emphasis on Applications to Civil and Environmental Engineering, 2nd Edition, John Wiley & Sons, Inc.

Alesch, D., Nagy, R., Taylor, C., (2002). Seeking Criteria For The Natural Hazard Mitigation Investment Decision, Acceptable Risk Processes: Lifelines and Natural Hazards, TCLEE, Monograph No.21, March 2002.

Bakersfield Californian. (1952). Earthquake Sparks Refinery Fire. Local Section. July 22, 1952.

Basoz, N., Kiremidjian, A., King, S., Law, K. (1999). Statistical Analysis of Bridge Damage Data from the 1994 Northridge, CA, Earthquake. Earthquake Spectra. Vol 15. No. 1, February 1999.

Bergman, E., Owen, N. (1952). Earthquake Damage Analyzed: Three Refining Plants in Kern County, California Surveyed after Arvin Quake of July, 1952. Petroleum Refiner. Vol. 33, No 3. March 1954.

Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthquake Spectra. Vol. 19, No.4, pages 733-752.

CBS. (2011). Cost estimate of San Diego power outage tops $100 million. Retrieved from: http://www.cbs8.com/story/15422811/2011/09/08/cost-estimate-of-san-diego-outage-tops-100-million

California Energy Commission. (2011). Weekly Fuels Watch Report. California Energy Commission: Energy Almanac.

Chang, S. (2000). Disaster And Transport Systems: Loss, Recovery, and Competition at the Port of Kobe After the 1995 Earthquake, Journal of Transport Geography 8, pgs 53-65

Chevron. (2013). The Early Years 1902 – 1914. Retrieved From: http://richmond.chevron.com/home/aboutchevronrichmond/history/history_early_years.aspx

Comerio, M. (1998). Disaster Hits Home: New Policy for Urban Housing Recovery. University of California Press.

Davis, C. (2013). Modeling Water System Services and Seismic Resilience. 2013 EERI Annual Meeting. February 14, 2013. Retrieved From: http://www.slideshare.net/EERIslides/modeling-water-system-services-and-seismic-resilience-craig-davis

Dahlhamer, J., Webb, G., Tierney, K. (1999). Predicting Business Financial Losses in the 1989 Loma Prieta and 1994 Northridge Earthquakes: Implications for Loss Estimation Research. University of Delaware Disaster Research Center. Preliminary Paper #282.

EBMUD. (2012). Earthquake Readiness, http://www.ebmud.com/sites/default/files/pdfs/Earthquake_Readiness_0.pdf

EBMUD. (2005). 10 Years of Accomplishments: 2004 2005 Progress Report. East Bay Municiapl Utility District Seismic Improvement Program. Retrieved From: http://www.ebmud.com/sites/default/files/pdfs/sip_annual_2005.pdf

EERI. (2013). Chirstchurch Earthquakes Workshop: Response and Recovery Lessons from the 2010-2011 Eartqhauek Sequence in Canterbury, New Zealand. Summary Report – February 12, 2013, Seattle WA. Retrieved From: http://2013am.eeri-events.org/wp-content/uploads/2011/09/ChristchurchWorkshopSummaryReport.pdf

EERI. (2010). The M 8.8 Chile Earthquake of February 27, 2010. EERI Special Earthquake Report. June 2010, Retrieved from: https://www.eeri.org/site/images/eeri_newsletter/2010_pdf/Chile10_insert.pdf

EERI. (1990). Introduction and Overview. Earthquake Spectra: May 1990, Vol. 6, No. S1, pp. 1-6.

Eidinger, J. (2004). Fire Following Earthquake – Flex Hose, 13th World Conference on Earthquake Engineering, Paper No. 3268, http://www.iitk.ac.in/nicee/wcee/article/13_3268.pdf

ESSBIO. (2010). Reconstruyendo Nuestro Servicio. Presentation. August 29, 2010.

FEMA. (1992) Earthquake Resistant Construction of Gas and Liquid Fuel Pipeline Systems Serving, or Regulated by, the Federal Government. Federal Emergency Management Agency. FEMA 233, NISTIR 4795

GEER. (2010). Geo-Engineering Reconnaissance of the February 27, 2010 Maule, Chile Earthquake. Version 2. May 25, 2010.

Hollenbeck, J. (2014). Discretization of Levee Systems Considering Spatial Autocorrelation of Levee Material Properties and Loading Conditions Respectively. PhD Dissertation, UC Berkeley.

Horwich, G. (2000). Economic Lessons of the Kobe Earthquake. Economic Development and Cultural Change. Vol. 48, No. 3 pp.521-542. The University of Chicago Press.

HSSA. (1983). Health Facilities: Alfred E. Alquist Hospital Facilities Seismic Safety Act, Section 1296780. Retrieved from: http://www.oshpd.ca.gov/fdd/seismic_compliance/SB1953/SeismicRegs/hssa.pdf

IEA International Energy Agency. (2012). Oil & Gas Security Emergency Response of IEA Countries: Chile. Retrieved From: http://www.iea.org/publications/freepublications/publication/Chile_2012.pdf

Johnson, L. (2013). Post-disaster Restoration of Water and Wastewater Systems: Lessons from Recent Studies and Disasters. Bay Area Critical Infrastructure Lifelines Restoration Workshop. October 7, 2013.

Johnson, Gayle. (2002). Refinery Damage and Emergency Response in the 1999 Izmit, Turkey Earthquake. Han-Padron Associates. California State Lands Commission Prevent First Symposium 2002. Retrieved From:

http://www.slc.ca.gov/Division_pages/MFD/Prevention_First/Documents/2002/Paper%20by%20Gayle%20Johnson.pdf

Kameda, H. (2000). Engineering Management of Lifeline Systems Under Earthquake Risk, 12th World Conference on Earthquake Engineering

Lee, M. (2012). SDG&E Customers file 5,000+ outage claims,11.7.2012 Retrieved From: http://www.utsandiego.com/news/2011/nov/07/over-5000-sdge-customers-seek-damages-september-ou/

Lienkaemper, J., Borchardt, G., Lisowski, M., (1991). Historic Creep Rate and Potential for Seismic Slip Along the Hayward Fault, California. Journal of Geophysical Research, Vol. 96, No. B11, pgs 261-283. October 10, 1991.

Leung, S., Yee, A., Wesemann, L. (1995). Northridge Earthquake Lifeline Performance and Post-Earthquake Response, Chapter 11: Transportation Overview, Technical Council on Lifeline Earthquake Engineering, Monograph No. 8.

Lewis, T., Mackin, T., Darken, R. (2011). Critical Infrastructure as complex Emergent Systems, International Journal of Cyber Warfare & Terrorism.

Mauldin, J. (2012). How Change Happens, Thoughts From The Frontline, Mauldin Economics, August 17, 2006, http://www.mauldineconomics.com/frontlinethoughts/how-change-happens

NTSB. (2011). Pacific Gas and Electric Company Natural Gas Transmission Pipeline Rupture and Fire San Bruno, California September 9, 2010. National Transportation Safety Board. Accident Report NTSB/PAR-11/01 PB2011-916501. Retrieved From: http://www.ntsb.gov/doclib/reports/2011/PAR1101.pdf

Nojima, N., Sugito, M. (2005). Probabilistic Assessment Model for Post-Earthquake Serviceability of Utility Lifelines and its Practical Application. Proceedings ICOSSAR 2005, Safety and Reliability of Engineering Systems and Structures.

Oliveira, C., Roca A., Goula, X. (2006). Assessing and Managing Earthquake Risk, Geo-Scientific and Engineering Knowledge for Earthquake Risk Mitigation: Developments, Tools, Techniques. Pg 210

Orth, D. (2011). Berkeley Aboveground Water Supply System BAWSS. PEER Annual Meeting 2011. Retrieved from: http://peer.berkeley.edu/events/annual_meeting/2011AM/wp-content/uploads/2011/10/Fire_Orth_David.pdf

Petersen, M. (2007). Probabilistic Seismic Hazard Analysis Problem. USGS Thailand Seismic Hazard Workshop. January 16-19, 2007. Retrieved From: http://earthquake.usgs.gov/hazards/about/workshops/thailand/downloads/Thailand-workshop-pshatraining1-new-.pdf

Phillips 66. (2013). San Francisco Refinery Public Affairs. Retrieved From: http://www.phillips66.com/EN/about/our-businesses/refining-marketing/refining/SFRPA/Pages/SFRPA.aspx

Porter, K., Jones, L., Cox, D., Goltz, J., Hudnut, K., Mileti, D., Perry, S., Ponti, D., Reichle, M., Rose, A., Scawthorn, C., Seligson, H., Shoaf, K., Treiman, J., Wein, A. (2011). The ShakeOut Scenario: A Hypothetical Mw7.8 Earthquake on the Southern San Andreas Fault. Earthquake Spectra. Vol 27, No. 2. May 20110.

Rose, A., Liao, S., Oladosu, G. (2007). Business Interruption Impacts of a Terroist Attack on the Electrical Power System of Los Angeles: Customer Resilience to a Total Blackout. Risk Analysis, Vol. 27, No. 3, 2007

Rose, A., Benavides, J., Chang, S., Szczesniak, P., Lim D. (1997) The Regional Economic Impact of an Earthquake: Direct and Indirect Effects of Electricity Lifeline Disruptions. Journal of Regional Science, Vol. 37, No. 3, 1997, pp437-458. Blackwell Publishers.

RMS. (2000). Event Report Kocaeli. Turkey Earthquake. Risk Management Solutions Reconnaissance Team. Retrieved From: https://support.rms.com/publications/Turkey_Event.pdf

San Francisco Lifelines Council. (2014). Lifelines Interdependencies Study | Report. April 17, 2014. The Lifelines Council. The City and County of San Francisco.

Sandalow, D. (2012). Hurricane Sandy and Our Energy Infrastructure. November 30, 2012. Retrieved From: http://energy.gov/articles/hurricane-sandy-and-our-energy-infrastructure

Scawthorn, C. (2011). Fire Following Earthquake Aspects of the Southern San Andreas Fault Mw 7.8 Earthquake Scenario, Earthquake Spectra Vol 27, Num 2

Schanack, F, Valdebenito, G, Jorge, A. (2012) Seismic Damage to Bridges during the 27 February 2010 Magnitude 8.8 Chile Earthquake, Earthquake Spectra Vol 28, No. 1 pp.301-315

Schiff, A. (1990). Lifelines, Earthquake Spectra: May 1990, Vol. 6, No. S1, pp.239-338

Schiff, A. (1998). Hyogoken-Nanbu (Kobe) Earthquake of January 17, 1995 Lifeline Performance. Technical Council on Lifeline Earthquake Engineering. ASCE. Monographic No. 14 September 1998.

Schremp, G. (2013) Personal Communication. August 13, 2013. Gordon Schremp, Senior Fuels Specialist for the California Energy Commission.

SFPUC. (2013). About WSIP. San Francisco Water Power Sewer, San Francisco Public Utilities Commission. Retrieved On: November 17, 2013. Retrieved From: http://www.sfwater.org/index.aspx?page=115

SFPUC. (2011). 2010 Urban Water management Plan for the City and County of San Francisco. San Francisco Public Utilities Commission. June 2011. Retrieved From: http://www.sfwater.org/Modules/ShowDocument.aspx?documentID=1055

Song, J., Ok, S. (2009). Multi-scale System Reliability Analysis of Lifeline Networks Under Earthquake Hazards, Earthquake Engineering and Structural Dynamics, 39:259-279

Song, J., Der Kiureghian, A. (2003). "Bounds on system reliability by linear prog ramming." J. Engineering Mechanics, ASCE, 129(6): 627-636.

Taylor, C. VanMarcke, E. (2002). Introduction, Acceptable Risk Processes Lifelines and Natural Hazards, Council on Disaster Reduction and Technicial Council on Lifeline Earthquaek Engineering. ASCE. Monograph No. 21 March 2002.

TCLEE. (2010). Technical Council on Lifeline Earthquake Engineering (TCLEE) Preliminary Report 27 February 2010 M8.8 Offshore Maule, Chile Earthquake. ASCE TCLEE. May 2010

Tierney, K., Nigg, J. (1995). Business Vulnerability To Disaster Related Lifeline Disruption, Preliminary Paper #223, University of Delaware Disaster Research Center

Tobolski, M., La Brie, J. (2011). Seismic Certification Requirements Enforcement and Practice, EERI Technical Seminar: Seismic Design and Performance of Nonstructural Elements. November 3, 2011.

Turner, L. (2011). ShakeCast: A Tool for Post-Earthquake Decision-making and Response. TCLEE 2011 Conference. Retrieved From: http://www.dot.ca.gov/researchconn/past_speakers/MrTurner/research_connection_shakecast_071408.pdf

UASI. (2014). Regional Catastrophic Earthquake Logistics Response Plan: Annex to the San Francisco Bay Area Regional Emergency Coordination Plan. OES ID 075-95017. Appendix G. Retrieved On: May 5, 2014 Retrieved From: http://www.bayareauasi.org/sites/default/files/resources/Regional%20Logistics%20Response_February%202014.pdf

USGS. (2012a). October 17, 1989 Loma Prieta Earthquake, Retrieved from: http://earthquake.usgs.gov/regional/nca/1989/

USGS. (2012b). The Parkfield, California Earthquake Experiment http://earthquake.usgs.gov/research/parkfield/index.php

USGS. (2000). Implications for Earthquake Risk Reduction in the United States from the Kocaeli, Turkey Earthquake of August 17, 1999. U.S. Geological Survey Circular 1193.

Wells, D., Coppersmith, K. (1994). New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. Bulletin of the Seismological Society of America. Vol. 84, No. 4, pp. 974-102, August 1994

Werner, S., Dickenson, S., Taylor, C. (1997). Seismic Risk Reduction at Ports: Case Studies and Acceptable Risk Evaluations. Journal of Waterway Port Coastal and Ocean Engineering 123, 6. 337-346.

Wittkop, D., Jensen, B. (2002). Communicating Acceptable Risk Analysis-An Owner/Engineer's Perspective, Acceptable Risk Processes: Lifelines and Natural Hazards, TCLEE, Monograph No.21, March 2002

WSJ. (2010). Chile Enap Restarts Bio Bio Refinery to Reduce Fuel Imports. Wall Street Journal. Retrieved from: http://wikileaks.org/gifiles/docs/871542_chile-energy-5-20-chile-enap-restarts-bio-bio-refinery-to.html

WSPA. (2013). Crude Oil Supply. Western States Petroleum Association. Retrieved On: 8/21/2013 Retrieved From: https://www.wspa.org/issues/crude-oil-supply

Yashinsky, M. (1998). The Lorna Prieta, California, earthquake of October 17, 1989-highway systems: U.S. Geological Survey Professional Paper 1552-B, 19 1 p.

Yashinsky, M. (1995). Northridge Earthquake Lifeline Performance and Post-Earthquake Response, Chapter 7: Bridges and Roadways, Technical Council on Lifeline Earthquake Engineering, Monograph No. 8

APPENDICES

APPENDIX A: CALIFORNIA STATE HAZARD MITIGAITON PLAN - ANNEX 3:

LIFELINES INFRASTRUCTURE AND HAZARD MITIGATION PLANNING

http://hazardmitigation.calema.ca.gov/docs/SHMP_2013_Annexes1-6.pdf

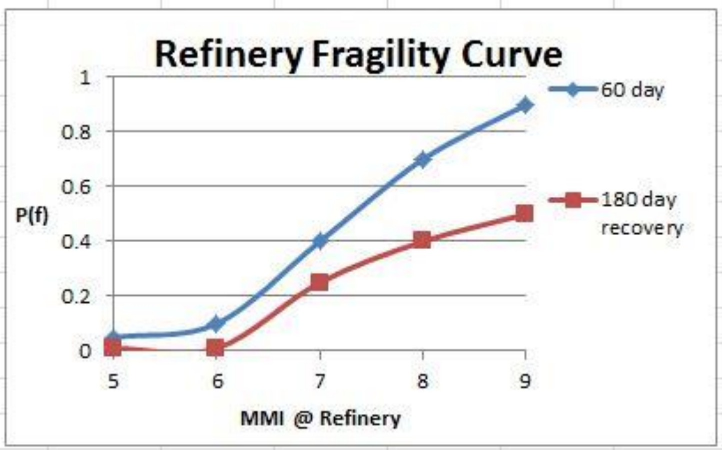
APPENDIX B: CASCADING FAILURES: EARTHQUAKE THREATS TO

TRANSPORTATION AND UTILITIES

http://resilience.abag.ca.gov/wp-content/documents/Cascading_Failures/InfrastructureReport_2014.pdf

APPENDIX C: MONTE CARLO SIMULATION SCREENSHOTS

							random number generators for each site					
						0.20565	0.644358	0.830289	0.311733	0.36244	0.254794	
						RandNum is compared against respective points on Fragility cu						
						Richmond	Rodeo	Benicia	Martinez	Martinez	Concord Station	
correlation	Refinery Fragility Curve				bls/day	245000	78000	132000	156000	166000	-	
1	MMI	60 day	180 day		regional s	0.315	0.100	0.170	0.201	0.214	-	
0.9	9	0.9	0.5	90								
0.8	8	0.7	0.4	0	Concord	6	7	8	8	9	8	
0.7	7	0.4	0.25	0	if stateme	0	0	0	180	180	180	
0.6	6	0.1	0.01	0	if for 90	0	0	0	0	0		0
0.5	5	0.05	0.01	0	if for 18	0	0	0	0.200772	0.213642		0.414414
0.4					Hayward	8	8	7	7	6	7	
0.3					if stateme	180	90	0	90	0	90	
0.2					if for 90	0	0.100386	0	0.200772	0		0.301158
0.1					if for 18	0.315315	0	0	0	0		0.315315
0					San Andre	8	7	7	7	7	6	
					if stateme	180	0	0	90	90	0	
					if for 90	0	0	0	0.200772	0.213642		0.414414
					if for 18	0.315315	0	0	0	0		0.315315



The values above have unique if statements that compare the random number against the fragility curve. The MMI for each refinery is set based on the refineries exposure in each discrete scenario.

Acceptance Curve

outage lei	min % of refineries interrupted
90 days	0.5
180 days	0.33

	Monte Carlo Simulations (1,000)						*Adds (90 & 180) for 90 or greate*			*Failure or No Failure*		
	Concord		Hayward		San Andreas		Concord	Hayward	an Andrea	Concord	Hayward	an Andreas
	90 Days	180 Days	90 Days	180 Days	90 Days	180 Days	90	90	90			
0	0	0.414414	0.301158	0.315315	0.414414	0.315315	0.414414	0.616474	0.72973	1	1	1
1	0.516088	0.383526	0.213642	0.485199	0	0.698842	0.899614	0.698842	0.698842	1	1	1
2	0	0.383526	0.27027	0	0.169884	0.213642	0.383526	0.27027	0.383526	1	0	0
3	0.169884	0.200772	0.301158	0.315315	0.200772	0.315315	0.370656	0.616474	0.516088	0	1	1
4	0.314028	0.370656	0.315315	0.471042	0.415701	0.370656	0.684685	0.786358	0.786358	1	1	1
5	0.200772	0.383526	0.27027	0	0.169884	0	0.584299	0.27027	0.169884	1	0	0
6	0.314028	0.370656	0.516088	0.27027	0.616474	0.169884	0.684685	0.786358	0.786358	1	1	1
7	0.213642	0.169884	0.169884	0	0.169884	0	0.383526	0.169884	0.169884	0	0	0
8	0.27027	0.213642	0.315315	0.100386	0.415701	0.213642	0.483912	0.415701	0.629344	0	0	1
9	0	0.584299	0.616474	0.169884	0.516088	0.169884	0.584299	0.786358	0.685972	1	1	1

Histogram Total 90

	Concord	Hayward	San Andreas
upper bin	90 Days	90 Days	90 Days
0.1	3	33	40
0.2	14	87	44
0.3	52	58	75
0.4	168	119	165
0.5	204	236	152
0.6	325	180	182
0.7	170	173	168
0.8	17	93	102
0.9	33	15	54
1	15	7	19

Histogram 90 & 180

	Concord		Hayward		San Andreas	
upper bin	90 Days	180 Days	90 Days	180 Days	90 Days	180 Days
0.1	213	146	304	192	368	182
0.2	156	112	205	189	136	117
0.3	262	256	121	123	140	161
0.4	173	235	196	199	195	212
0.5	100	146	99	157	64	122
0.6	67	81	46	86	69	116
0.7	24	21	27	44	19	54
0.8	3	1	2	11	8	21
0.9	1	2	1	0	2	14
1	2	1	0	0	0	2

upper bin	
0.1	0
0.2	0
0.3	0
0.4	0
0.5	0
0.6	0
0.7	0
0.8	0
0.9	0
1	10

Cumulative Values

Concord		Hayward		San Andreas	
90 Days	180 Days	90 Days	180 Days	90 Days	180 Days
3	146	33	192	40	182
17	258	120	381	84	299
69	514	178	504	159	460
237	749	297	703	324	672
441	895	533	860	476	794
766	976	713	946	658	910
936	997	886	990	826	964
953	998	979	1001	928	985
986	1000	994	1001	982	999
1001	1001	1001	1001	1001	1001