TRANSPORTATION SYSTEM DEMAND AND PERFORMANCE IMMEDIATELY AFTER AN EARTHQUAKE

by

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ABSTRACT

Transportation systems are a class of critical civil infrastructure systems that must be able to respond to disruptions while continuing to provide mobility as well as reduce both human and property loss when disasters occur." In the aftermath of these catastrophic events, emergency response trips are among those most sensitive to delay. Considering the importance of the emergency trips and the special case of a damaged network after a disaster, the goal of this research is to develop a method to evaluate the performance of the transportation system, specifically for emergency response trips, after an earthquake.

The first step in reaching this goal is to understand the particulars of the hazard itself and how the transportation system should be prepared. A limited number of earthquake scenarios, representing specific historical data and the possible events that occur in the aftermath, have been chosen to represent the hazard. The impact of each of these scenarios on the transportation components – specifically, bridges – is estimated in this research. In the following step, models predicting a number of emergency response trips have been developed, followed by both supply and demand side is simulated with a macro simulation software. Travel delay and other measures to evaluate the performance of the transportation system are also calculated. Lastly, areas susceptible to the greatest delay for emergency response trips are identified and countermeasures to reduce the delay are proposed.

This method is used for two case studies: one in Newark, Delaware, and one in the San Fernando Valley of California. The Newark case study is used to understand

the application of the methodology using a familiar network even though the area is not inherently vulnerable to earthquakes. The results of the analysis are as expected with relatively minor impacts. The San Fernando Valley case study used forty-nine earthquake scenarios. The analysis underscored the difficulties of accessing some of the more remote parts of the network, identifying areas underserved by medical and fire centers, and identified bridges that could impact the effectiveness of emergency response. While emergency response trips are relatively small in number, the analysis demonstrates that in some areas these trips may be significantly impacted by disruption to the transportation network. These disruptions require understanding the demand for emergency response trips and understanding how these trips use the transportation network.

Chapter 1

INTRODUCTION

Transportation systems are planned to provide service over a wide range of conditions including after natural disasters, such as earthquakes, hurricanes and floods, or manmade disasters like terrorists attacks. Most transportation planning efforts aim to maximize the performance or level of service under normal operating conditions. However, after a disaster, the relationship between supply and demand, and the demand and supply themselves, will change. The assumptions made for normal operations are not necessarily valid anymore, but we understand very little about how the transportation performs immediately after a disaster. In such situations new models are needed to predict the efficiency of the transportation system. These models and their outputs can be used to plan ahead for the aftermath in order to improve the transportation network, making it more resilient to disasters while minimizing the level of disruption.

This research aims to better understand how transportation systems function immediately following a disaster. This knowledge can then be used to identify investments that will mitigate the impact of disasters on the transportation system, improve emergency response times, and improve the performance of the transportation network in this period.

Studies of the post-disaster supply side of transportation systems include how the transportation system components like bridges, tunnels, and pavement resist the forces imposed by the hazard or fail, and the effects of their loss of functionality on the network performance as a whole in these abnormal circumstances. The methods used to predict the condition of individual elements in the transportation systems for each of these hazards are unique to the specific hazard based on the hazard's nature and features. However, given the transportation network (supply side), most of the activities immediately after a disaster are similar in terms of how the transportation infrastructure is used. For example, the transportation network is needed for search and rescue operations, firefighting, and transferring patients. Therefore, we can hypothesize that demand models can also be used for a wide range of hazards. Nevertheless, in this research, earthquakes in particular are studied, and the system condition and performance after an earthquake are investigated.

Recent studies have focused on modeling the supply side of the transportation system after an earthquake using probabilistic risk analysis methods. These studies have been successful in capturing both the probability of failure of transportation elements and the whole system performance considering the disrupted elements (Kiremidjian, Moore, Fan, Yazlali, Basoz, & Williams, 2007), (Başöz & Kiremidjian, 1995), (Shiraki, Shinozuka, Moore, Chang, Kameda, & Tanaka, 2007). However, these studies either do not deal with demand immediately after disaster at all or simply makes the assumption that demand for the transportation system is the same before and after an earthquake. Therefore, this dissertation focuses on:

- Developing traffic demand models to understand the changes in traffic on the network
- Using these demand models, along with damage to the network (that is, changes in supply) to predict the system performance after a severe event

The transportation demand immediately after a disaster considers both emergency response trips taken by agencies responsible for emergency services and trips by individuals. The part of the transportation demand, which is generated by emergency responders, is easier to estimate because the purpose of these trips is more obvious. For the purpose of this study, only the emergency response trips are studied in detail, in order to serve as a first step in developing post-disaster demand models. These models are developed based on in-depth study to understand the process of each emergency response operation. Unlike traditional demand models for an activity, which are empirically derived, historic data representing the number of trips for developing or evaluating this model is not available. The demand models are then used with models of network supply to estimate flow and delay. These models help to understand the impact of an event on network performance.

1.1 Problem Statement

Transportation systems are a class of critical civil infrastructure systems that must be able to respond to disruptions and continue to provide mobility as well as reduce both human and property loss when disasters occur. Therefore, understanding and modeling transportation systems after a disaster are vital for emergency managers, and government agencies to mitigate, prepare for, respond to, and recover from the potential impact effectively. Like other systems, the transportation system has two sides: supply and demand. These two sides are in equilibrium for the system under normal operation, but after a disaster, both parts of this equilibrium will change. The supply side of transportation systems can be measured by metrics like capacity and free flow speed. These metrics are investigated and analyzed in the disaster management literature using risk assessment methods. In contrast, transportation demand immediately after a disaster has drawn less attention. This research focuses on developing travel demand models for the special case of post-disaster demand, followed by understanding the interaction between supply and demand, and the impact on network performance.

1.2 Objectives

The overall objective of this study is to estimate performance measures for an entire network after an earthquake, using current supply models and a newly developed demand model. These models can be used in mitigation and preparedness phases to plan ahead for the post-disaster situation with the intent to minimize the level of disruption. The end result is to present the most effective strategies to enhance the network functionality after an earthquake.

The secondary objectives are:

- Develop travel demand models for the response period after an earthquake
- Integrate existing transportation supply models with these new demand models to assess network performance
- Develop case studies demonstrating the role of these models in mitigation and preparedness

1.3 Motivation

Awareness of disasters increases when large scale events occur, such as Hurricane Katrina and the Great East Japan Earthquake (Sendai, Japan, 2011). For the Sendai Earthquake, physical damage has been estimated to be between $195 and $305 billion. More than 27,000 people were killed or are still missing, and more than 202,000 homes and other buildings were totally or partially damaged (NHK World , 2011). As a result, much of Japan’s transportation network suffered severe disruptions. Many sections of Tohoku Expressway, which serves northern Japan, were severely damaged when the earthquake hit on March 11, 2011. The expressway did not reopen to general public use until 24 March 2011 (Nanto, Cooper, & Donnelly, 2011). All railway services were suspended in Tokyo, with an estimated 20,000 people stranded at major stations across the city. Consequently, the snarled transportation system hobbled the distribution of essential medicines and equipment (Valeo, 2011).

Providing medical aid, dispatching rescue teams and supplies, and performing debris removal are vital emergency response operations after a disaster like this. However, transportation system services are not confined to emergency response after the disaster. A reliable transportation system can be designed if the system's functionality and performance after a disaster is understood and rigorously analyzed. To understand the transportation system performance after a disaster, like other systems, predicting both the supply of and demand for transportation is necessary.

1.4 Overview of Methodology

As mentioned, the objective of this research is to estimate the demand for the transportation system and the performance of the system after a disaster. Understanding the hazard is the first element in this analysis. Hazards are basically defined by two components: intensity and probability. Models to predict the hazard based on historic data and the locations of faults are first reviewed. The next step is the impact of expected hazard on the supply side of the transportation system. In a post-earthquake case, the damage to the bridges, tunnels and pavement sections are the impact of an earthquake on the supply side of the transportation network. Sophisticated methods are developed to estimate the damage to the components of the transportation system for expected hazards. The damage to the transportation network decreases the functionality of the system. The relationship between the damage state and the functionality of the system is addressed using metrics, like capacity. The reduction in capacity of these components is based on their damage state and is also studied in the previous literature (Shiraki, Shinozuka, Moore, Chang, Kameda, & Tanaka, 2007).

The demand side of the system is divided to two categories: emergency response trips and individuals' trips. The number of emergency response trips generated is estimated based on data and information regarding the structure and function of emergency operations, and some logical assumptions for each emergency operation. The number of individuals' trips is approximated with peak hour traffic (Lamb & Walton, 2011). These emergency response trips and an approximation of individuals' trips are added to the network.

Finally, the system performance is analyzed with the post-earthquake supply and demand using macro simulation software. System performance measures, like travel time and delay for emergency response trips, are also calculated. This methodology is applied to two case studies (Newark, DE. and San Fernando Valley, CA.).

1.5 Scope and Assumptions

The transportation system studied in this research is confined to road networks and the effect of an earthquake is investigated on the road network for the first hour immediately after the disaster strikes. The earthquake is assumed occur during the afternoon. It is assumed that in this period of time, only the local resources are available and regional, state and federal assistance will be activated after this period. The local resources are also assumed to be adequate. The number of trips generated by emergency response operations is studied and estimated in this research. A rough estimation of trips made by individuals' trips is made based on previous studies. The impact of debris on road network capacity is not considered.

1.6 Outline of the Dissertation

This introductory chapter presents the problem statement, objectives and motivation for this research. The second chapter presents the literature review. The third chapter is the methodology. The following two chapters are case studies demonstrating the application of the methodology. The sixth chapter is a discussion of the methods and results. The final chapter presents a summary, conclusions, directions for future work and contributions. An appendix includes a survey to gather empirical data to estimate demand for emergency response trips.

Chapter 2

BACKGROUND LITERATURE: MODELING CHANGES IN THE TRANSPORTATION NETWORK

This chapter reviews the relevant literature on modeling changes in a transportation network following an earthquake. After defining transportation networks, studies in the areas of changes in supply and demand of a transportation system after an earthquake are covered. For the supply side, only the research related to earthquake hazards is covered; for the demand side, because there are few studies related to earthquakes, a brief review of the transportation system studies following other disasters is provided. Reviewing the previous work in this area helps us to find the most appropriate models and methods to predict the hazard, the effect of hazards on the network and on travel demand, and estimate the performance of the network after an earthquake. Moreover, the shortcomings of current methods in estimating the travel demand immediately after an earthquake will be discussed.

2.1 Defining a Network

> "A network is referred to as a pure network if only its topology and connectivity are considered. If a network is characterized by its topology and flow properties (such as origin-destination demands, capacity constraints path choice and link cost function) it is then referred to as flow network. A transportation network is a flow network representing the movement of people, vehicle or goods. Any transportation network can be represented as a graph in the mathematical sense, consisting of a set of links and a set of nodes. The links represent the movement between the nodes, which in turn represent points in space". (Bell & Lida, 1997)

> "For the roadway network nodes are mostly intersections and links are streets through which traffic moves". (Sheffi, 1984)

The transportation system is modeled as a network to capture the relationships between and among the users and the physical elements. A trip in a transportation network corresponds to a flow with a distinct origin (or starting point) and destination (or end point). In transportation, networks are represented with different levels of detail in terms of the sources of trips, the potential end points and whether all links are modeled or simply main roads.

The performance of the transportation network is influenced by the changes in transportation supply and demand; in the following sections previous studies in the area of transportation supply and demand, and the models to estimate the changes in each side following a disaster are reviewed.

2.2 Supply

> "Supply is expressed in terms of infrastructures (capacity), services (frequency) and networks (coverage). The number of passengers, volume (for liquids or containerized traffic), or mass (for freight) that can be transported per unit of time and space is commonly used to quantify transport supply" (Sheffi, 1984).

Models of supply are reviewed in this section. Transportation supply is the capacity of transportation infrastructures and modes, generally over a geographically defined transport system and for a specific period of time. The models presented here concentrate on transportation system supply in terms of condition after an earthquake. The models rely on a two-step process, the first of which assesses the hazard and damage, the second of which estimates the impact of the hazard and damage on link capacity.

2.2.1 Hazard Assessment

Risk analysis is performed in the first step of modeling the transportation network after a disaster. Risk analysis is about identifying the drivers, assessing their likelihood of occurrence and their potential consequences (Kirchsteiger, 1999).

Prior to 1968, the only method for assessing seismic risk for an area was deterministic, which only considers the worst-case scenario. For example, in a seismic risk analysis, the deterministic method considers one earthquake event from a specific source (historical event). The maximum credible impact on the various system elements is computed, largely based on expert judgment. Deterministic approaches produce an “all or nothing” type of assessment (i.e., the system is found to be “safe” or “unsafe”) (Kirchsteiger, 1999).

Probabilistic earthquake risk analysis was first formalized by Cornell (Cornell, 1968). The method known as probabilistic seismic hazard analysis (PSHA) is intended to quantify the rate (or probability) of exceeding various ground-motion levels at a site (or a map of sites) given all possible earthquakes (Field, 2005). In other words, PSHA is the evaluation of annual frequencies of exceedance of ground motion levels (typically designated by peak ground acceleration or by spectral accelerations) at a site. The result of a PSHA is a seismic hazard curve (annual frequency of exceedance vs. ground motion amplitude) or a uniform hazard spectrum (spectral amplitude vs. structural period, for a fixed annual frequency of exceedance) (Kirchsteiger, 1999). The probabilistic approach would consider the hazards from “all” possible seismic sources that may impact a particular site and how often the events may occur. Besides the magnitude of each possible event, it considers explicitly the probability of occurrence (Kirchsteiger, 1999).

The important point is that PSHA gives the opportunity of choosing the level of the risk that can be tolerated and the risk tolerance can be changed based on external variables such as budget. However PSHA is designed to analyze the risk for a single site or a map of sites and fails to capture the spatial correlation between earthquake ground motions across many sites.

Chang, Shinozika and Moore (2000) presented a methodology by which probabilistic risk analysis method can be extended to the assessment of urban lifeline systems.

> "The methodology first identifies a limited set of deterministic earthquake scenarios and evaluates infrastructure system-wide performance in each. It then assigns hazard-consistent probabilities to the scenarios in order to approximate regional seismicity; the resulting probabilistic scenarios indicate the likelihood of exceeding various levels of system performance degradation. This methodology provides a means for selecting representative earthquake scenarios for response or mitigation planning." (Chang, Shinozuka, & Moore, 2000)

2.2.2 Impact Assessment

The second step in modeling a transportation network after an earthquake is estimating the impact of an earthquake on the system's components or overall system performance. Models of change in the transportation system supply are generally based on the analysis of bridge failure on the whole system performance. Reduced capacities, due to debris and road segment failure, have been neglected in most studies.

Fragility curves for bridges are developed based on this idea. A fragility curve describes the conditional probability that a bridge reaches at least a given damage state as a function of ground motion. The damage states most commonly used in the literature are: (1) no damage; (2) minor damage; (3) moderate damage; (4) major damage and (5) complete damage. Thus, any fragility curve is defined for a given damage state. Both empirical and analytical methods are used in developing these curves (McGuire, 2008).

Fragility curves are used to determine the most vulnerable bridges and prioritizing bridges for retrofitting (Başöz & Kiremidjian, 1995). This idea is used in a system-wide risk analysis. Applying the idea of whole system analysis and using fragility curves Kiremidjian et al (Kiremidjian, Moore, Fan, Yazlali, Basoz, & Williams, 2007) presented a method to estimate total loss for a deterministic scenario. Total loss includes direct loss (cost of repair of individual components) plus costs associated with time delays due to detours from route closures. In this method, direct loss is calculated based on the damage state of all the bridges in the network due to the scenario earthquake. To calculate indirect loss, the only assumption is that bridges in damage state of 3, 4 or 5 (moderate, major, and complete damage) are considered to be closed.

In a more comprehensive study, Shiraki et al. (Shiraki, Shinozuka, Moore, Chang, Kameda, & Tanaka, 2007) extended the idea of fragility curves to whole system performance in their paper, "System risk curves: probabilistic performance scenarios for highway networks subject to earthquake damage". This study uses Chang et al's (Chang, Shinozuka, & Moore, 2000) method to identify representative earthquake scenarios and their hazard-consistent likelihood. Then applying fragility curves, the BDI (bridge damage index), as devolved solely from the bridge damage state, is estimated. The LDI (link damage index) is presented for the first time in this study. LDI is developed to explain the state of a transportation link based on the damage states of all the bridges in that link. Four states are assigned to the links based on their LDI:

(1) No damage;

(2) Minor damage;

(3) Moderate damage, and

(4) Major damage.

The authors assigned a portion of capacity and free flow speed for each state of link damage. The relationship between the links' damage state and the links' free flow speed and capacity is not supported by any kind of analytical or experimental data. This study served as a pioneering example for applying probabilistic methods in earthquake-related disruption estimation.

Later, Stergiou and Kiremidjian (2010) used a similar method and extended Kiremidjian's (Kiremidjian, Moore, Fan, Yazlali, Basoz, & Williams, 2007) study to probabilistic scenarios. They used a US Geological Survey model to develop all possible earthquake events and the probability for them. They also considered the recovery of bridges over time in their study.

A different type of analysis of the transportation system's supply side is used in a model for optimizing the distribution of first aid commodities (Barbarosoglu & Arda, 2004). In this paper, hazard assessment and impact estimation are presented as the two stages of a model. The authors identify the earthquake hazard using a finite number of earthquake scenarios and their likelihood. In the second stage, the various impacts of each scenario with their probabilities are considered. The advantage of this model is its flexibility by time. After an earthquake, the earthquake scenario is determined and the only uncertainty is in assessing the impact. These impact scenarios can change as time goes on after an earthquake and uncertainty gradually turns to certainty. This is a useful model for the response period, however the size and complexity of the model, which considers every single probable earthquake scenario, makes it inappropriate for mitigation or planning purposes (Barbarosoglu & Arda, 2004).

2.3 Demand

> “Transport demand is the transport needs, even if those needs are satisfied, fully, partially or not at all. Similar to transport supply, it is expressed in terms of number of people, volume, or tons per unit of time and space.” (Sheffi, 1984)

This section presents a review of demand models, beginning with conventional demand models, which estimate the demand for transportation network under normal operating conditions. Later, the broader area of transportation demand after different kinds of disasters is investigated. These models serve as a foundation for demand models for the time period after an earthquake.

2.3.1 Conventional Demand Models

> “The history of demand modeling for person travel has been dominated by the modeling approach that has come to be referred to as the four step model (FSM). Travel, always viewed in theory as derived from the demand for activity participation, and in practice has been modeled with trip-based rather than activity-based methods. Trip origin-destination (O-D) rather than activity surveys form the principle database.” (McNally, 2000)

The four sequential steps of the model are:

- *Trip generation*: Measures of trip frequency are developed providing the propensity to travel. Land use characteristics (i.e. how we use land in a region) is the main determinant of trip generation rates. This is because factors like the number and size of households, automobile ownership, types of activities (residential, commercial, industrial, etc.), and density of development all drive how much travel flows from or to a specific area within the region. For simplicity, a geographic unit called a transportation analysis zone (TAZ) is used to create trip generation rates for the region. Specifically, a number of existing or projected characteristics within the TAZ are used for this (Bell & Lida, 1997).

- *Trip distribution*: Trip productions are distributed to match the trip attraction distribution and to reflect underlying travel impedance (time and/or cost), yielding trip tables of person-trip demands. The analysis involves a sophisticated process for weighting the "attractiveness" of each TAZ based on the number of attractions it has and the travel time from other TAZs. This step leads to a picture of origin and destination points within the region and how many trips are going between each pair of TAZs.

- *Mode choice*: Trip tables are essentially factored to reflect relative proportions of trips by alternative modes.

- *Route choice*: Modal trip tables are assigned to mode-specific networks. Route choice determines the routes people will take from start (origin) to finish (destination). Generally, the model assumes everyone will take the quickest route to their destination. This is complicated by the fact that as routes become congested, alternative routes may represent the shortest path. To compute route selection requires all kinds of information regarding actual or predicted congestion levels, road conditions, transit schedules and fares, traffic signal systems, etc.

The time dimension (time of day) is typically introduced after trip distribution or mode choice where the production-attraction tables are factored in to reflect observed distributions of trips in defined periods (such as the a.m. or p.m. peaks). In route choice, performance characteristics are first introduced, thus, the FSM in its basic form only equilibrates route choices. In other words, total "demand", as specified through generation, distribution, mode choice, and time-of-day models, is fixed, with only the route decision to be determined. Most applications of the FSM feedback equilibrated link travel times to the mode choice and/or trip distribution models for a second pass (and occasionally more) through the last three steps, but no formal convergence is guaranteed in most applications (McNally, 2000).

The conventional four-step modeling framework has some inherent weaknesses, including having a trip-based sequential structure with limited behavioral responses that often ignore time-of-day dimension. Additionally, the trip generation step is usually unresponsive to congestion and pricing and consequently unresponsive to most demand management measures (Zargari, Araghi, & Mohammadian, 2009).

Two ideas in modeling travel demand have evolved from FSM. The first is the recognition that the representation of the trip decision as a sequential process is not completely realistic. It has been argued that the trip decision should be modeled simultaneously without resorting to an artificial decomposition into sequential stages. The second development was the introduction of a probabilistic demand model that relied on a more realistic theory of choice among qualitative trip alternatives (Ben-Akiva, 1973). It has been shown for a standard linear regression model that an aggregation of the data prior to estimation will result in a loss of precision of the estimated parameters if the aggregate groups are not homogeneous with respect to the value of the explanatory or independent variables (Cambridge Systematics, 1998). More precise models are presented using micro level data. These are called disaggregate travel demand models that are policy-sensitive and consistent with travel choice theory using data at the level of individual travelers.

Aggregate and disaggregate travel demand models are sometimes viewed by transportation planners as mutually exclusive or competitive approaches to the forecasting problems, while some researchers argue this idea and see them as complimentary. The assumption behind aggregate models is that there is an identical choice environment for all individuals in a zone. Aggregate models should forecast accurately under this homogeneity condition, but cannot be expected to succeed when zones are heterogeneous. Disaggregated behavioral models provide a theoretical foundation for the aggregate models and represent conditions under which the aggregate models will give valid forecasts. The aggregate models may provide the most convenient means of forecasting when zonal homogeneity condition is met (Bowman & Ben-Akiva, 2001).

2.3.2 Extreme Event Demand Models

> "Traffic modeling in extreme events was first studied in the 1970s for hurricane evacuation. The focus was shifted to nuclear power plant evacuation after the 1979 Three Mile Island accident but was directed back to hurricanes again in the 1990s. Earthquakes-related traffic modeling has drawn attention lately, especially after the recent tsunamis and earthquakes in Asia. The staged model is the most widely accepted approach to describe the traffic demand modeling under hurricane and nuclear hazards. The first stage is to estimate travel demand by using the number of at-risk population and its response to evacuation orders, then trip distribution models are employed to generate trip matrix with gravity model or manual assignment. The second stage, also known as network loading stage, is to load the travel demand to the transportation network with models that simulate the departure time. Modeling the travel demand and traffic following earthquakes is much more complex than hurricane or nuclear-related hazards, partially due to the fact that post-earthquake travel demand is coupled with the deteriorated capacity of post-earthquake transportation infrastructures. Additionally, public response to earthquake is distinct because prior warning for earthquakes is usually unavailable or infeasible, which makes the post-earthquake traffic pattern less dependent on the behavioral response or network loading model" (Chang, Elnashai, & Spencer Jr, 2012)

It has been noted that the pre-earthquake travel demand was inappropriate for evaluating the post-earthquake performance of transportation networks (Shiraki, Shinozuka, Moore, Chang, Kameda, & Tanaka, 2007). A set of studies in the area of modeling transportation systems after an earthquake confines the transportation system demand to logistic purposes. The idea is that, after a disaster the demand of the system is dispatching commodities (medical materials, specialized rescue equipment, rescue teams, etc.) to distribution centers in affected areas as soon as possible to accelerate relief operations. However, two different strategies to deal with “relief demand” (the demand for medical materials, food, equipment and rescue teams) are recognized in these studies. The first strategy assumes the system’s demand as an external input and work with pre-identified demand for the network (Knott, 1988), (Rathi, Church, & Solanki, 1992.), (Haghani & Oh, 1996), (Ozdamar, Ekinci, & Kuckyazaci, 2004), (Nolz, Doerner, Gutjahr, & Hartl, 2010), and (Lin, Batta, Rogerson, Blatt, & Flanigan, 2011). The other one develops a forecasting model for the demand for relief in the form of supplies such as food, water and shelter (Sheu, 2007) and (Zhu & Cao, 2010).

Another set of studies estimates the long-term changes in travel demand, primarily as a part of economic loss caused by earthquake. Two major causes for the changes in travel demand after an earthquake are identified. The first is change in travel time and relevant travel cost because of supply reduction, travel rate for each household or firm will change based on new travel cost. The second reason for changes in travel demand is the damage to buildings, including residential, commercial and industrial areas. For this second cause, the travel rates are considered to be fixed, but changes in the number of households or firms induce changes in travel demand.

An example for estimating the travel changes based on travel cost is presented in Tatano and Tsuchia’s paper (2008). In this paper, trips are divided between firms’ trips (freight) and households’ trips. For each of these categories, an economic model to maximize the profit or utility is developed. In these models, the number of trips generated is dependent on the trip cost. After the earthquake, the trip cost will be updated based on the changes in supply side of the system. The optimum number of trips that maximizes the profit will also be estimated. In this study, the recovery of links in time is considered and the capacity is adjusted. The same concept is used to estimate the travel demand after an earthquake in REDARS (Risks from Earthquake Damage to Roadway Systems) (Moore, Cho, Fan, & Stuart, 2006). Described as "a public-domain software package that accounts for how earthquake damage affects post-event traffic flows and travel times, and estimates losses from these travel-time and traffic-flow impacts," (Werner) REDARS recognizes changes in demand based on changes in travel times. In a report for the Pacific Earthquake Engineering Research Center (Moore, Cho, Fan, & Stuart, 2006) the variable demand method used in REDARS is described. In this method, the demand is assumed to be dependent on the travel time. The models to estimate travel demand rate for each trip purpose are developed and calibrated.

Examples of change in building areas after an earthquake that causes changes in travel demand can be seen in Shinozuka et al. (Shinozuka, et al., 2005) work. In this study, the reduction in the "usable floor area of buildings" is the main reason for reduction of the trips produced or attracted to a specific zone. After an earthquake, because of the damage to the building, the usable floor area will be reduced.

All these studies assume that the purpose of the trips is the same before and after the earthquake, which is applicable when the emergency period has passed and people's activity returns to normal. However, immediately after an earthquake, the trip purposes differ from those of a regular day. Chang et al. (2011) started considering the changes of trip purposes after an earthquake. They tried to modify the travel demand matrix representing normal conditions to estimate the post-earthquake demand. In their method, they considered trips seeking medical support and temporary shelters as post-earthquake trip purposes. Therefore, the number of trips attracted to zones with hospitals/shelters is increased based on the capacity of the center. For the areas with damaged buildings, new trips with the purpose of evacuation are produced, but the number of trips attracted to these zones is reduced.

2.3.3 Demand for Emergency Response Trips

This study is to develop a demand model for emergency response trips by emergency responders immediately after an earthquake. The research produces estimates of travel demand for specific disaster response activities. Based on a handout published by the Federal Emergency Management Agency (Martin), disaster response activities typically include:

1. Rapid damage assessment
2. Search and rescue
3. Emergency medical care
4. Emergency restoration of essential services
5. Fire-fighting
6. Emergency communications
7. Crisis decision-making
8. Evacuation, protection of lives and property
9. The provision of emergency shelter for victims
10. Debris removal
11. Other

Each emergency response activity, as related to the trips generated by these activities, is discussed below. Many of the trip estimates depend on estimates of the earthquake damage; the extent and severity of damage can be assessed using Hazus-MH, which is a tool developed by FEMA to provide such estimates and is subsequently described in more detail in Section 2.4.1.

2.3.3.1 - Rapid damage assessment

Damage assessment plays a vital role during the initial minutes and hours of disaster response operations. Emergency response activities, such as the dispatch of search and rescue groups and firefighters, and providing medical services, are done based on the extent and intensity of damage. The first perception of damage intensity is created in the rapid damage assessment reports. This procedure helps to identify the immediate needs of disaster victims (e.g., emergency medical care, sheltering). It also enables first responders and emergency managers to recognize the required materials and human resources. This procedure is conventionally done through “windshield survey” or “drive by” evaluation throughout a geographical area to quickly provide an overview or “snapshot” of what has occurred (Ganz, 1998). More recent research encourages the use of new science and technology like airborne laser scanning (Markus, Fiedrich, Gehbauer, & Hirschberger, 1999) and satellite image processing. When large scale disasters occur in the US, local fire departments typically answer initial calls for help, thus rapid damage assessment is a part of the fire department’s responsibility.

For example, in the case of the 2003 Paso Robles earthquake in San Simeon, California, an initial damage assessment was conducted by the fire department immediately after the event in order to evaluate safety concerns and to begin mobilizing resources. As time progressed, the County Office of Emergency Services gathered residential damage assessment data from the Red Cross, as well as all other types of damage and loss estimates from local governments and businesses in the area. The Red Cross, the fire department, and public works department performed the initial damage assessment in vehicles. In conducting their initial damage assessment, many different county agencies utilized planes and helicopters for an aerial damage assessment, which covers a large geographic area and is often the preferred means of politicians. Damage assessments are consequently not only varied but are undertaken via distinct methods as well. For instance, the Red Cross utilized an initial damage assessment to determine the number of personnel that would need to be called in to carry out more detailed appraisals later on. When these human resources arrived, the more comprehensive assessment could then take place (McEntire & Cope, 2004).

Reviewing the windshield survey process, and especially the possibility of replacing new methods, leads us to hypothesize that the number of trips generated by this activity is very limited and can be included in firefighting operations.

2.3.3.2 - Search and rescue

The search and rescue (SAR) task, which involves rescuing people from collapsed buildings, is another important emergency response operation after disaster. Trips taken by emergency responders to accomplish this task are a significant part of emergency response trips loaded on transportation networks immediately after an earthquake. These trips are important because of their quantity and emergency nature. Any collapsed building should be served first and this task should be done expeditiously as the fatality rate increases as a function of time.

Models to estimate demand for search and rescue equipment and personnel are not discussed much in previous studies save for one particular German study. In this study (Schweier & Markus, 2004), the influencing factors on SAR demand for collapsed buildings are identified by surveying international search and rescue organizations, as well as reviewing after action reports related to SAR activities. Their findings show that the demand for SAR resources is highly dependent on the damage type and for large building with a large number of occupants, it depends on the number of people trapped within. They also provided an estimate of hours worked per trapped victim, for which the severity of damage is an influencing factor.

Given the severity of damage for buildings for each earthquake scenario by Hazus-MH (our reference for building damage assessment after an earthquake), we could survey emergency managers (or fire departments) to determine the resources (personnel and vehicles) needed for each type of damaged building. The damaged building is categorized based on damage severity, number of stories, and occupancy density. Once the resources necessary to perform SAR for each type of building are identified, the number of trips to each zone can be estimated by considering the number of damaged buildings and the quantity of available resources in each resource center (fire station). The trips can then be assigned to the network assuming that the fire department minimizes the time to take all the trips.

2.3.3.3- Emergency medical care

Trips involving emergency medical care are taken to transfer injured people to medical centers. To find the number of trips loaded to the network, the first step is finding the number and severity of casualties in each traffic zone (census tracts in this research).

Based on estimated distributed ground motion, the estimated number of casualties typically follows one of three alternative procedures, described as empirical, semi-empirical, or analytical models. An empirical model uses fatality data from past earthquakes to estimate a fatality rate based directly on the level of ground shaking. A semi-empirical model first uses the local estimate of ground shaking to estimate the collapse rate (and perhaps heavy damage) rate for each of a number of different building classes based on empirical damage data. It then distributes the population among the different building classes according to the time of day of the event, and estimates a fatality (and perhaps injury) rate for each building class, given collapse or heavy damage. An analytical model is essentially the same as a semi-empirical model, except that collapse rates are based on an analytical procedure, such as Hazus-MH.

In this research, Hazus-MH is used to estimate number of casualties and their severity. In Hazus-MH, four levels of severity are defined for casualties, labeled 1 through 4. By definition, severity levels 2 and 3 need hospitalization. Predicting the number of medical trips in this analysis is based on summation of the number of level 2 and level 3 casualties. After finding the total number of people that need to be transferred to medical centers in each census tract, the hourly number of trips to transport all the injured is needed. The hourly distribution (by percentage) of people extracted from damaged structures and transported was investigated for the Kobe Earthquake by Kuwata and Takada. Two trips (from and to the medical centers) for each injured person are loaded on the network to represent the transportation of injured to medical centers after the earthquake.

2.3.3.4 - Emergency restoration of essential services

Essential services in this research include water, wastewater, oil, natural gas, electric power, communication, and transportation, and all are lifelines needed to be restored after an earthquake. The repair process for some of these lifelines, like the transportation system, offers two kinds of repair plans after a major disaster: 1- long term repair for complete restoration, which can take months or perhaps years; 2- short term repair, which are hasty and just sufficient enough to carry out disaster relief work and may take a few days (Yan & Shih, 2007). In this research, the short-term restoration is investigated for all essential services to estimate the transportation demand with the purpose of restoration of lifelines immediately after the earthquake.

Restoration tasks to restore a water system are identified by Tabucchi et al. for Los Angeles, California. They include:

- Inspection;
- Rerouting around trunk line damage;
- Isolating distribution line damage;
- Repair.

To find the number of trips loaded onto a transportation system to accomplish these tasks, some factors should be known or estimated:

- The water system expanse (number of regulator stations, tanks, and reservoirs, the total length of pipelines)
- The number of crew needed for water system inspection based on the expanse of the system
- The estimated damage on the system, such as number of leaks and breaks for pipelines

- The number of crews needed for rerouting, isolating and repair based on estimated damage
- The number of crews available to complete each task
- Any consideration for scheduling tasks (day and night shifts)

Knowing all these parameters, the number of trips taken by crews to their work station can be estimated by the number of available/needed number of crews in each time segment (considering one trip per person). The destination zones are the location of work station, and it is assumed that the original zones are the same as the ones for pre-earthquake work trips. This means that the proportion of work trips originating in each zone and ending in a destination zone (work station) is considered the same for pre and post-earthquake conditions. The number of trips from workstations to other zones to inspect or repair the system basically depends on the restoration plans and the real restoration process. In the case of the water system, the number of leaks and breaks for each pipeline section can be found using Hazus-MH, then the number of crews available/needed to repair the pipelines can be dispatched from their individual work station to the damage location.

Restoration tasks to restore an electrical power system are identified by Cagnan et al. (2007), which describes power restoration tasks for Los Angeles. These tasks are categorized under four important sections:

- Initial inspection;
- Damage assessment;
- Repair;
- Re-energizing.

The important factors to find the number of trips for this system are similar to the ones for the water system.

For both of these systems, the authors to simulate the condition of system during the restoration period also provide discrete event models. These models can also be used to estimate number of crews needed and their time schedule.

Based on these studies, generally restoration has two major phases:

1. Inspection: For which the expanse of the system and the available crew are the most important factors in finding the number of trips.
2. Repair: In this phase, both the system's expansion and crews, and the magnitude of earthquake, is important to estimate the damage.

For oil, natural gas, transportation, and communication systems, interviews with the emergency response authorities for each section would be needed to understand the restoration process and determining the tasks to be performed, and number of trips needed for accomplishing the tasks.

2.3.3.5 - Firefighting

The fire department is a department with many high level responsibilities after a disaster, such as an earthquake. In previous sections, it was stated that the first task firefighting personnel should complete immediately following an earthquake is "rapid damage assessment". After large disruptive disasters like earthquakes, communication systems are not reliable, so most of the fires ignited immediately after an earthquake are located by the firefighters as opposed to people calling in the events (Beall, 1996). Furthermore, search and rescue is another emergency response operation firefighters must complete in post-earthquake scenarios; controlling and extinguishing fires is also discussed.

Generally, the first wave of fires starts simultaneously just after the main shock. For the Kobe earthquake, 50% of fires in the first day started within 14 minutes after the earthquake (Beall, 1996). With this high level of incidents occurring almost immediately following the earthquake, the result is a highly concentrated load on the transportation network. However, the number of trips to accomplish the firefighting task is directly dependent on the personnel and apparatus available.

To estimate the traffic demand for the purpose of firefighting, the location of fire stations, number of personnel on duty and the total number of personnel are needed. Moreover, an estimation of the number of fires and extent of area covered by fires in each zone (or census tract) is needed. There are various types of models available that simulate fire ignition and the spreading of fires after an earthquake. Hazus-MH uses these models to estimate the loss caused by fire after earthquake. The output of the Hazus-MH model is the number of ignitions and the burned area for each census tract.

The factors that affect the number of personnel and vehicles needed to control the fire and an average number based on the extent of fire should be found by surveying fire department experts.

Some of the factors that may have important effects on the number of personnel and vehicles needed are:

- The source of ignition (this factor is not identified in the Hazus-MH model; if found as an influential factor, Hazus-MH models should be replaced by a more appropriate one)
- The density of population and buildings in each census tract (besides the burnt area from Hazus-MH)
- The building's material (wood, steel, etc.)

The number of personnel and vehicles needed in each census tract and the location of the fire stations provide the required input to determine the number of trips.

2.3.3.6 & 2.3.3.7 - Emergency communications and Crisis Decision making

These two activities are not directly dependent on the transportation network. Any trips required to complete these two tasks are ignored.

2.3.3.8 & 2.3.3.9 - Evacuation, protection of lives and property, and the provision of emergency shelter for victims

These two tasks are directly dependent on people's behavior and their choice to make evacuation trips. It is more appropriate to estimate these trips along with other individuals' trips after a disaster to have more precise results. The provision of emergency shelter for victims also requires consideration of behavior.

2.3.3.10 - Debris removal

Disasters can generate large volumes of debris, which can severely impact emergency response and recovery efforts (Brown & Milke, 2009).

Collection operations are normally broken into two phases: response and recovery. An efficient debris management plan includes collection activities for response and recovery debris strategies. Response occurs sometimes during and always immediately after an event in order to clear emergency access routes. The recovery operation usually begins after the emergency access routes are cleared. Then, the residents return to their homes and begin to bring debris to the public rights-of-way (Federal Emergency Management Agency, 2007).

Debris removal activities during the response phase include immediate actions for the removal of debris to facilitate search and rescue efforts, to allow access to critical facilities, and prevent flooding. Actions required during the response phase are usually completed within a matter of days following a disaster event (Federal Emergency Management Agency, 2007)

Prior to and immediately following the event, extricating people and providing access to health care facilities are the top priorities; therefore, the major arterial routes are given priority to emergency services staff like police, fire, and ambulance services. Emergency operations infrastructure, such as the emergency operations center and supply distribution centers, normally are the next priority.

Hazus-MH uses the severity of damage for buildings to determine the total volume of the debris created. While surveying emergency responders, those surveyed should be asked about the percentage of debris removed on the first day; knowing the volume of debris can determine an estimate of the number of personal and vehicles required. For the purposes of this study, we are assuming that there is no debris removal in the first hour following the event.

2.3.3.11 - Other activities that take place during the immediate post-impact emergency period.

Any special activities can be studied and the number of trips for those activities can be added to the current estimated traffic.

2.3.4 Individuals' Trips

To evaluate the performance measure of the transportation system after an earthquake, the demand for the system should be estimated. Individuals' trip purposes include:

- Meeting people, including reconnecting with, checking on and assisting family and friends;
- Assessing property damage;
- Moving to higher ground;
- Meeting job responsibilities;

- Gathering information.

Although only the emergency response trips are studied and methods to estimate the number of trips for that purpose are presented, individuals' trips should be considered in estimating the performance measure of the system. Therefore, the number of individuals' trips is estimated based on previous studies.

In a recent study by Lamb and Walton, the travel behavior of individuals after the 2007 Gisborne Earthquake was examined (Lamb ad Walton, 2011). The study is based on a simulation model and a real survey after the earthquake. The trips taken in the 48 hours after the earthquake were considered and some interesting facts were discovered. The findings of Lamb and Walton's study that can be used in predicting individuals' trips were:

- 85% of people experienced the earthquake at home
- Traffic volumes approximated peak weekday conditions within an hour of the event
- 37% of people had traveled within three hours of the event
- Nearly all trips were undertaken in motor vehicles
- People initially travelled to meet other people and assess property damage
- Respondents reported a median departure time of 25 minutes after the event, with 85% of trips undertaken within one hour of the event

These findings were obtained from a survey performed after a moderate earthquake in Gisborne, New Zealand. In another study (2009), Walton and Lamb state: "Contrary to what you would expect, more people travel if the event is less severe. That means our transport system has to cope with more traffic if we have a moderate event as opposed to a major event."

Based on these studies, our analysis uses the peak weekday conditions to approximate the trips by individuals.

2.4 Tools to Support the Analysis

Two important tools are used in the analysis. The first is Hazus-MH in order to assess earthquake damage, while the second is network modeling software. Both are described here.

2.4.1 Hazus-MH

> "Hazus is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes. Hazus uses Geographic Information Systems (GIS) technology to estimate physical, economic, and social impacts of disasters" (FEMA, 2014).
>
> "Hazus damage functions for ground shaking have two basic components: (1) capacity curves and (2) fragility curves. The capacity curves are based on engineering parameters (e.g., yield and ultimate strength) that characterize the nonlinear (pushover) behavior of 36 different model building types. For each of these building types, capacity parameters distinguish between different levels of seismic design and anticipated seismic performance. The fragility curves describe the probability of damage to the buildings: (1) structural system, (2) nonstructural components sensitive to drift and (3) nonstructural components (and contents) sensitive to acceleration. For a given level of building response, fragility curves distribute damage between four physical damage states: Slight, Moderate, Extensive and Complete." (Department of Homeland Security, Federal Emergency Management Agency)
>
> "Building damage is used as an input to a number of loss modules, including the estimation of casualties, direct economic losses, displaced households and short-term shelter needs, and loss of emergency facility function and the time required to restore functionality." (Department of Homeland Security, Federal Emergency Management Agency)

Casualties caused by a postulated earthquake can be modeled by developing a tree of events leading to their occurrence. As with any event tree, the earthquake-related casualty event tree begins with an initiating event (earthquake scenario) and follows the possible course of events leading to loss of life or injuries. The state of damage of buildings and the probability of being in that state, besides the casualty rate for each damage state, were used to estimate number of casualties. Data for earthquake related casualties were relatively scarce, particularly for U.S. earthquakes. Therefore, to some extent the casualty rates are inferred from the available data statistics and combined with expert opinion (Department of Homeland Security, Federal Emergency Management Agency).

The damage state for the bridges in the network was also estimated using Hazus-MH, which uses bridge inventory data to classify the bridges based on their seismic design. Using fragility curves allows us to estimate the damage state of each bridge based on the earthquake scenario. The damage state of the bridges will be used as an output from Hazus-MH in this study.

A critique of Hazus-MH is beyond the scope of this research. Hence the assumptions inherent in Hazus-MH are also a limitation of this work.

2.4.2 Cube

The transportation macro simulation software Cube is used to model the network and evaluate the performance measures.

> “Cube is the world’s most widely used and most complete suite of software products for transportation planning. Cube has a broad range of exceptional, easy to use capabilities for the comprehensive modeling of transportation systems. With Cube you can analyze and estimate the impacts of a wide range of infrastructure improvements and operating

> policies. Cube generates decision making information quickly by using powerful modeling and GIS techniques, statistics and comparisons, clear reports and descriptive graphs and high quality graphics and animations. Cube empowers users to make smarter decisions quickly by uncovering key indicators to use when evaluating planning alternatives". (Citilabs)

The transportation system before an earthquake for both case studies were modeled in Cube, and the network changes were made for each earthquake scenario. The inter-zonal travel time for all these scenarios was calculated by Cube.

Similar to the use of Hazus-MH, a critique of Cube is beyond the scope of this research. Important limitations of the macro-analysis used in Cube is the fact that all trips originate or end at the zone centroid, intra-zonal trips are not considered in measures of delay and the use equilibrium assignment of trips to the network is dependent on standard travel time functions.

2.5 Performance Measures

System performance measures are important for several reasons. First, they enable comparisons of system conditions across disaster events in different urban areas. They facilitate the development of a generalized, rather than case study specific understanding, of earthquakes and their impacts. Second, they allow comparisons across disaster event scenarios for a single study region. With the emergence of computerized earthquake loss estimation models, regional disaster scenarios can now be rapidly developed and used for pre-event mitigation planning. Summary system performance measures are useful in this context for evaluating the degree of system improvement afforded by various levels of bridge retrofits and other mitigation actions. This aids mitigation prioritization under budget constraints. Performance measures may also facilitate discussions of what levels of risk and potential loss are acceptable or unacceptable. Third, system performance measures can be used in designing efficient post-disaster restoration strategies by prioritizing damage repair, such that overall system performance can be optimized. Finally, system performance measures can be implemented for estimating economic impacts in the context of real-time earthquake loss models for emergency response and recovery planning. Summary measures can serve where detailed databases and sophisticated transportation models are not available for rapid post-disaster analysis (Ayothiraman & Hazarika, 2008).

Travel time was chosen as the basic performance measure in another study (Chang, Shinozuka, & Moore, 2000). Other common performance measures for travel time reliability (Lyman and Bertini, 2007; McLeod, Elefteriadou, and Jin, 2012) are not relevant as the post disaster situation is not a repeated event.

Chapter 3

METHODOLOGY

The methodology described in this chapter was developed to address the research objective – to estimate network performance after an earthquake and to then identify the most effective strategies to enhance the network functionality after an earthquake. The following methodology draws on the literature discussed in Chapter 2. The implementation of this methodology and the interpretation of the results requires many assumptions. As a result, the research is exploratory in the sense that it provides an estimate of the magnitude of the changes in performance and identifies areas for further research. This chapter presents an overview of the methodology, reviews the assumptions, and then elaborates on each of the steps.

3.1 Overview

The proposed methodology has four steps.

1. Hazard Estimation – This step involved choosing appropriate earthquake scenarios. Two approaches were used
    - A deterministic analysis was done for a limited number of well-defined scenarios representing weak, medium and severe hazard.
    - A scenario analysis was conducted using a set of representative scenarios. Each scenario was identified with their relevant probability that could then be used instead of the whole range of probable scenarios to compute the expect cost and impacts.
2. Supply Changes – This step used Hazus-MH to determine the damage to bridges, after which the bridge damage state was estimated for each bridge and the resultant reduction in link capacity is calculated based

on Shiraki's work (2007). New capacities and free flow speed for links are determined based on the post-earthquake condition (damaged network).

3. Demand Estimation – Demand models were derived based on this research and the literature to estimate the number of trips between origins and destinations.
4. Performance Evaluation – Undamaged and damaged networks are simulated using macro level transportation planning and operations software. Performance measures were used to identify elements requiring risk mitigation.

3.2 Assumptions

As discussed, the methodology and the implementation to a real network require many assumptions. This section review the network level assumptions. The specific assumptions made are summarized after each step in the methodology is described.

Overall, the methodology assumed that a network model of the transportation system was available and that the links with bridges can be located to determine the damage. It was also assumed that the traffic flow on the network during a typical peak hour was known. Regions, either transportation analysis zones (TAZs) or census tracts, were used to determine how many trips were generated to and from a specific area.

3.3 Step by Step Methodology

3.3.1 Step 1 - Hazard Estimation

The deterministic versus probabilistic method was discussed in the literature review. The probabilistic method recognized all the historic and possible events along with their probabilities. Representative scenarios were a short list of credible events with probabilities assigned to them in the way that they reflect the whole list. Essentially, this means the impact of the short list considering their probabilities is the same as the comprehensive list of possible scenarios.

In this analysis we use the deterministic method and a scenario based method to characterize the hazard. For the Newark case study, since the area is not earthquake prone and there is no historic data for the area, three hypothetical deterministic scenarios, including major, medium and small earthquakes, are used. For the San Fernando Valley case study, representative scenarios from Chang et al. (2000) are used. Although we do not use the probabilities of the earthquake scenarios for the San Fernando Valley case study, subsequent evaluation could use the probabilities in an economic or financial evaluation of the costs and consequences.

This step assumes that the scenarios are an adequate representation of the earthquake hazard in terms of the magnitude, and location of a potential earthquake.

3.3.2 Step 2 - Supply Change

Hazus-MH was used to estimate the changes to the network – the supply side. The first sub-step was to determine the damage to the bridges, while the next sub-step was to determine how the link capacity changes based on the bridge condition.

Hazus-MH used the earthquake scenarios (from Step 1) as input and applies fragility curves for bridges to estimate the damage state of each bridge in the transportation network. Based on Hazus-MH and standard fragility curves, the damage states for bridges are: None, Slight, Moderate, Extensive, and Complete. Hazus-MH output for bridge damage was in the form of probabilities for the bridge being in each damage state and the probability for exceeding each damage state.

After estimating the damage state of each bridge in the study area, it was important to know how this damage to the bridge affects the traffic capacity of the bridge and consequently the whole network. The reduction in traffic capacity of a damaged bridge in this study is estimated based on the work of Zou et al. (2010). The residual capacity of the bridge for each damage state is shown in Table 1. The expected value of residual traffic based on the probability of being in each damage state after a scenario earthquake is used as the post-earthquake link capacity for the link carrying the bridge. For the links including more than one bridge, the minimum expected bridge capacity was used as the post-earthquake link capacity. Moreover, considering local network detours, the capacity of a bridge never reached zero in this method.

This step assumes that:

- Hazus-MH accurately predicts the ground shaking in the study. Assumptions made in using Hazus-MH include:
    - Setting the time of day to the afternoon peak hour.
    - Land slide and after shock is not considered
    - The fragility curves capture the extent of damage.
    - The relationship between damage state and capacity reduction is based on the work of Zou et al (2010).

Table 1 Reduction in Link Capacity Based on Link Damage

Link Damage State	Capacity (%)
No damage	100
Minor damage	75
Moderate damage	50
Major damage (Extensive)	25
Collapse (Complete)	10

3.3.3 Step 3 - Demand Estimation

Given that the focus of this research is on understanding how the transportation network functions during emergency response, this period was defined as the first hour following the event, because the research shows that the trips generated in the first hour were the most critical and most sensitive to delay. Two types of trips will be loaded on the network after the earthquake. The first type was trips related to the emergency response, the second type was trips by individuals for different purposes. In this research, trips for emergency response operations were studied and a method to estimate the demand for post-disaster emergency trips was suggested. The individual trips, however, are approximated by the peak hour traffic on a regular day (Lamb & Walton, 2011). The emergency operations considered in this research are those most sensitive to time, including medical response, firefighting, and search and rescue trips. Next, the method to estimate the number of trips for each emergency operation is elaborated.

3.3.3.1 Medical Trips

As discussed in the literature review, the number of casualties in each TAZ or census tract is estimated using a procedure embedded in Hazus-MH. Hazus-MH estimates the number of heavily damaged or collapsed buildings with the same fragility curves discussed before, then the rates of casualties based on the severity of the damage and the type of building were used to estimate the number of casualties.

Four levels of severity were defined for casualties. By definition, severity levels 2 and 3 need hospitalization. So, predicting the number of medical trips in this analysis was based on summation of the number of casualties for level 2 and level 3 casualties. After finding the total number of people that need to be transferred to medical centers in each census tract, the hourly number of trips to transport injured in the first hour is needed. There were two resources used to determine the number of trips taken in the first hour of the Kobe Earthquake and the Northridge earthquake. For the Kobe, the hourly distribution (by percentage) of injured people extracted from damaged structures and transported was analyzed by Kuwata and Takada (2004). The maximum hourly percentage of people transported to medical facilities is 30% of the total injured. However, the report for the Northridge earthquake (US Fire Administration) suggested that sufficient resources were available to respond to all injured immediately.

In this research, for the Newark case study, the damage was assumed to be more similar to the Kobe Earthquake, overwhelming the system. Therefore, only 30% of the total injured requiring transportation was transported to medical centers in the first hour. For the San Fernando Valley case study, it was assumed that the total number of injured were transported to the medical center in the first hour. It as also assumed that number of ambulances was enough to serve the hourly demand. Two trips, one to and one from the medical centers for each injured person, were loaded on the network to represent the transportation of injured to medical centers after the earthquake.

The step assumes that:

- Hazus-MH provides a reasonable estimate of the number of injuries.
- Adequate resources are available to transport the injured to the hospital.
- The trips do not extend beyond the hour under consideration.
- The distribution of trips by time after the event is consistent with the observations made during the Kobe earthquake.

3.3.3.2 Fire Fighting

The number of trips for firefighting operations was in direct relation with the number of ignitions based on the rate of ignition and building floor areas. In this research, one trip was assigned to each ignition. The number of ignitions was predicted using the method described in Hazus-MH for each TAZ or census tract. An empirical equation was used in Hazus-MH to predict the number of ignitions based on the peak ground acceleration and total floor area for each census tract. The specific equation is:

$$\text{Ign./TFA} = 0.581895\,(\text{PGA})^2 - 0.029444\,(\text{PGA}) \quad (1)$$

Where Ign./TFA is the mean number of ignitions per million sq. ft. of building total floor area in each census tract,

TFA is the total floor area, which is also extracted from Hazus-MH, and

PGA is the peak ground acceleration.

Once the number of ignitions for each census tract is determined, the number of trips can be estimated.

This step assumes that:

- The estimates of floor area are appropriate.
- The ignition rate is adequately modeled as a function of peak ground acceleration.
- The estimates of the number of completely damaged buildings are appropriate.
- The trip generation rates for the number of ignitions and number of damaged buildings of each type are representative.
- The distribution of trips over time are similar to the observations from the Kobe earthquake.

3.3.3.3 Search and Rescue

The number of trips for search and rescue operations was then estimated. The number of completely damaged buildings was estimated using Hazus-MH. For each completely damaged building, it was assumed one urban search and rescue company was sent from the closest fire center. Then, based on the characteristics of the building (concrete and steel or wood) the number of personnel to respond to that building was identified based on Table 2 (US Fire Administration/National Fire Academy, 2010). It was assumed that concrete and steel buildings use either type 1 or type 2 resources and wooden building were using resource type 3. Therefore, for concrete and steel buildings, six people should be transported to the site. It was assumed that two trips were made to transfer the apparatus and six personnel to the location of the damaged buildings. For wooden buildings, one trip was assigned to transfer the apparatus and three personnel to each damaged building. The number of search and rescue trips was in direct relationship with the number of completely damaged buildings in each zone and these trips' origin was within the closest fire center. For Newark, an assumption similar to the assumption for medical trips based on the Kobe model was used. This assumption assigned 15% of the total number of search and rescue trips to the first hour. Similarly, all search and rescue trips were assigned to the first hour for the San Fernando Valley case study.

Table 2 Personnel Resources Assigned to Search and Rescue Operation (Modified from ICS 420-1)

	Type 1 (Heavy)	Type 2 (Medium)	Type 3 (Light)	Type 4 (Basic)
US&R Crew	6	6	3	3

3.3.3.4 Validation

Validating the final demand model should be done using actual data from a recent earthquake. The Northridge earthquake was considered as an appropriate event for validation. We intended to gather as much data from Northridge as possible to use as a validation case for our method. A survey (shown in Appendix B) was also designed to evaluate the accuracy of our assumptions. Unfortunately, we could not manage to find the appropriate responders to the survey because too much time has passed since the event. Given that the data was not available in the form needed, we used logical processes to validate the methodology.

3.3.4 Step 4 - Performance Evaluation

The evaluation of the network before and after a hypothetical earthquake helps to understand what elements of the network may need hardening or other mitigation strategies, such as developing redundant paths in the network.

3.3.4.1 Selection of Performance Measures

The basic outputs from a network analysis are travel time or speed on each link. Given that the network has many links and a comparison on a link-by-link basis for different scenarios was unlikely to yield insight, we selected specific performance measures to identify scenarios of interest and then measured to indicate network performance.

To estimate the total loss caused by an earthquake, one of the important factors is the total system delay. In this study, delay was the difference between travel time for the undisrupted and the damaged network. Travel Delay (TD) is the difference of these two travel times for all origin and destination zones times the number of trips between these two zones.

$$TD = \sum_{j \in M} \sum_{i \in N} (t'_{ij} - t_{ij}) * V_{ij} \qquad (2)$$

Where t'_{ij} is the travel time between zones in the damaged network,

t_{ij} is the travel time between zones in the undisrupted network.

N is the set of origins and

M is the set of destinations, and

V_{ij} is the number of emergency response trips between zone j and zone j.

In this research, a performance measure, the Disruption Index (DI), was also defined to compare network performance in the damaged condition with the undisrupted condition. The measure basically compared the total travel time between each pair of zones before and after damage of the transportation system by the earthquake. The changes in the travel time for critical O-D pairs can be used to identify problematic paths and, in turn, problematic links. This is similar to the

Degradation Index, which is the ratio of the sum of shortest distances between nodes for the damaged network over the same parameter for the undisrupted network (Chang, et al., 2000) but captures both changes in supply and demand. Disruption Index (DI) is defined based on this travel time:

$$DI = \frac{\sum_{j \in M} \sum_{i \in N} (t'_{ij})}{\sum_{j \in M} \sum_{i \in N} (t_{ij})} \qquad (3)$$

Where t'$_{ij}$, t$_{ij}$, N, and M are the same as Equation (2)

Alternatively, the Disruption Index could be computed using vehicle minutes rather than just travel time, we call this performance measure Revised Disruption Index (RDI), where:

$$RDI = \frac{\sum_{j \in M} \sum_{i \in N} (t'_{ij}\, V_{ij})}{\sum_{j \in M} \sum_{i \in N} (t_{ij}\;\, V_{ij})} \qquad (4)$$

Where V$_{ij}$ is the number of emergency response trips between zone j and zone j following the earthquake.

3.3.4.2 Develop Simulation

To demonstrate the use of these models, a network simulation was developed. The simulation used the current and disrupted transportation network, as well as the estimated demand for the system, and estimates the performance measures, such as the travel time between zones for the damaged and undamaged cases.

Using user equilibrium method the background trips and emergency response trips are assigned to the network links. The performance of the network, such as total delay, was calculated with Cube for the damaged and undamaged cases.

3.3.4.3 Interpreting the Results

Results were used to

1- Identify the most problematic zones. These were zones with the greatest delay for emergency response trips. The reasons for delay were further discussed, and either an alternative road, retrofitting the bridges, or the establishment of a new medical or fire center, was proposed
2- The overall performance of the network based on the DI and RDI was evaluated.

The evaluation step assumes that:

- Individual's trips on the network are approximated by the afternoon peak hour trips.
- The incremental assignment of the emergency response trips based on user equilibrium capture the delays on the network.

Chapter 4

CASE STUDY: NEWARK

4.1 Introduction

Post-earthquake travel metrics cannot be inferred from normal operations because both supply and demand have been disrupted. Studies of the post-event supply of transportation systems focused on how components like tunnels, bridges and pavements withstand earthquake forces, and predicted the systems' condition based on the intensity and location of the event (Shiraki, Shinozuka, Moore, Chang, Kameda, & Tanaka, 2007). Very little research had focused on the demand side (Başöz & Kiremidjian, 1995). Recognizing this gap in knowledge, this case study explored the application of methods to predict the number of trips for emergency response operations and estimate travel metrics for these trips. Our objective was to use existing models, logical assumptions related to the demand for emergency trips, and network performance measures to quantify the impact of an earthquake on emergency response trips, and to assess the adequacy of the network for emergency response. The analysis was used to identify zones that were not well served or require additional resources.

The chapter is organized as follows. The following section outlines how the methodology developed in the previous chapter was applied to this case study. The case study is described and the methodology was applied to the case study and the delay determined. The chapter concludes by summarizing the results of the exploration.

4.2 Case Study Methodology

As described in Chapter 3, the methodology was built around existing models and tools to assess damage, model impacts, estimate demand, model the changes to the transportation network to understand the impact on travel time. The research built a preliminary assessment of changes to travel time using a hypothetical situation for emergency trips, by modeling three hypothetical earthquake scenarios and recognizing the differences in travel times of emergency response trips (Rahimian & McNeil, 2012). The network was an actual urban area, although that area was not in an earthquake prone area.

In this chapter, three hypothetical deterministic earthquake (5, 6, and 7 M_w) scenarios are considered. They are described as small, medium and major earthquakes for a city in the United States. This method can be modified to use probabilistic earthquake scenarios for actual earthquake-prone areas.

Applying Hazus-MH, "a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes" (Department of Homeland Security, Federal Emergency Management Agency), the damage to bridges, the number of casualties for each census tract, the number of damaged buildings, number of possible ignitions, and number of leaks and breaks for the water system and number of damaged substations for the power system were estimated.

Using these data, a model begins to form showing the reduction in the capacity of the transportation network (supply side) and the trips generated to transfer the injured to medical services, for firefighting and search and rescue (demand side).

Having the post-earthquake capacity and number of emergency response trips, the post-earthquake network was modeled in macro simulation software (Cube). It was assumed that the number of trips made by individuals (other than emergency response trips) matched the number of peak hour trips (Lamb & Waltom, 2011). The network was first loaded with these individuals' trips, and then emergency response trips were added to the loaded network. The number of emergency response trips was estimated for each operation separately. The emergency operations considered in this paper were: transferring injured people to medical centers, firefighting, search and rescue, and utility restoration. The travel time for emergency response trips for both before and after the earthquake was calculated and changes in travel time were monitored.

4.3 Overview of the Case Study Area

The city of Newark, Delaware, with a population around 31,000 and area of about 23 square kilometers, was used to explore the changes in transportation demand and supply following an earthquake. The city, however, does not have a history of earthquakes. Access to the network and an understanding of the flow patterns and resources were important in this hypothetical study in order to explore the interactions between the network condition (supply) and the demand for emergency trips. The study area is shown in Figure 1. The city has nine census tracts. Three fire stations are located in tracts 10003014200, 10003014502 and 10003014403 and a hospital is located in tract 90003, which is external to the city of Newark. The network model was based on Delaware Department of Transportation's planning model and was implemented in Cube.

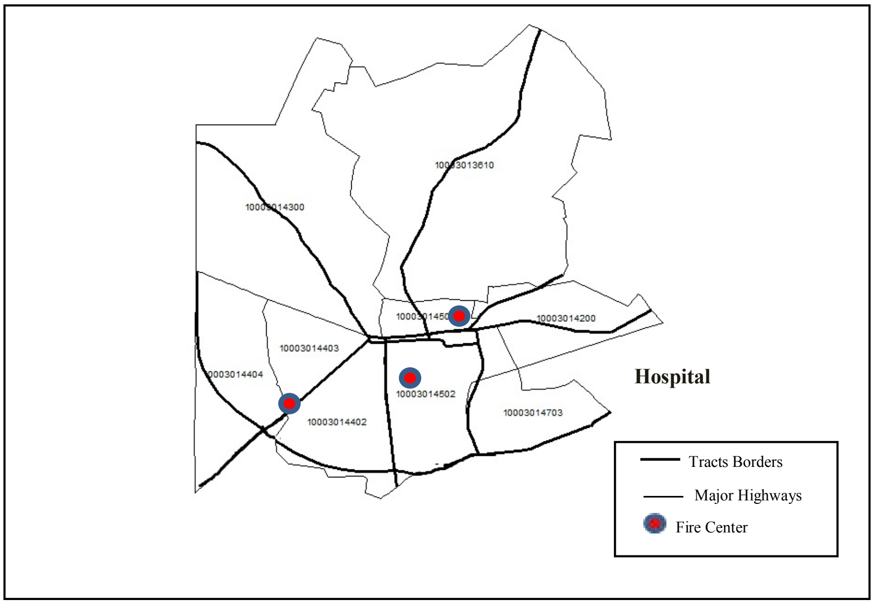


Figure 1 Study Area with Tract Numbers

Three earthquakes with magnitude 5, 6, and 7 on the Richter scale and epicenter of 20 miles from the city center and at a depth of 10 km were considered as the small, medium and major earthquake scenarios respectively for the City of Newark. These were hypothetical scenarios, as this network was not likely to be subjected to earthquakes, but analysis was intended to help us understand the impact on post-earthquake response. One hospital and three fire centers were considered as the trip generation/attraction for emergency response trips. The regular peak hour travel time and traffic were considered as the base network load (Lamb & Walton, 2011), and the emergency response trips from/to attraction points to/from all census tracts were added to the network. Also, the difference between travel time for the undisrupted and damaged network for emergency response trips was calculated. Travel delay as an indication of the network performance was estimated. The larger values of travel delay indicate larger human and property loss could be expected in the area after a disaster. The utility system restoration was not included for this case study since the data for the city of Newark is not available in Hazus-MH and our earlier assessment suggested that these trips were not significant.

4.4 Earthquake Impacts

The impacts of our three hypothetical earthquakes (major, medium and small) were modeled to estimate the impact on the network (supply) in terms of the reduction in bridge capacity, and demand generated, in terms of the number of firefighting, medical and search and rescue trips carried out.

4.4.1 Supply: Bridge Capacity Reduction

The residual capacity of each bridge in the study area was determined based on the damage state determined from Hazus-MH and the mapping from the damage state to residual capacity. Table 3**,** Table 4 and Table 5 show the expected residual capacity for the bridges for the selected scenario. Figure 2, Figure 3 and Figure 4 show the expected residual capacity on the map. The bridge capacity reduction represents the change in supply in terms of the damage to the network. For the major earthquake, 17 bridges were damaged, with the residual capacity of the damaged bridges ranging from 26% to 75%. For the moderate earthquake, the same 17 bridges were damaged, but the residual capacity ranges from 43% to 95%. For the small earthquake, only 10 bridges were damaged and residual capacity ranges from 83% to 99%.

Table 3 Residual Capacity after a Major Earthquake

Bridge ID	Residual Capacity
DE000040	74%
DE000342	72%
DE000345	73%
DE000347	26%
DE000349	75%
DE000366	75%
DE000367	75%
DE000368	75%
DE000370	60%
DE000387	75%
DE000390	75%
DE000391	74%
DE000460	58%
DE000484	60%
DE000485	72%
DE000486	72%
DE000497	56%

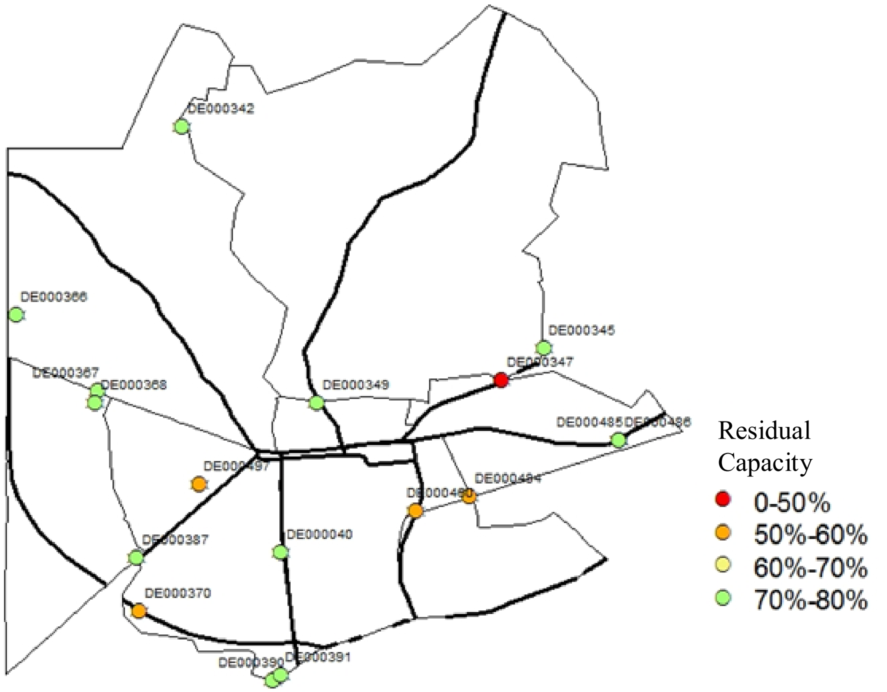


Figure 2 Residual Capacity for Bridges after a Major Earthquake

Table 4 Residual Capacity after a Medium Earthquake

Bridge ID	Residual Capacity
DE000040	91%
DE000342	95%
DE000345	89%
DE000347	43%
DE000349	93%
DE000366	96%
DE000367	95%
DE000368	95%
DE000370	85%
DE000387	93%
DE000390	90%
DE000391	89%
DE000460	79%
DE000484	79%
DE000485	86%
DE000486	86%
DE000497	84%

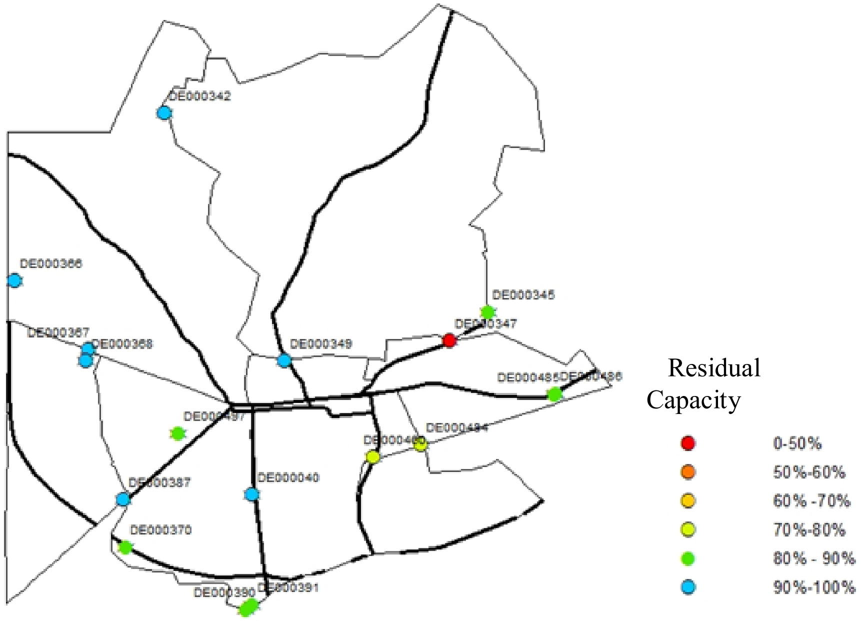


Figure 3 Residual Capacity for Bridges after a Medium Earthquake

Table 5 Residual Capacity after a Small Earthquake

Bridge ID	Residual Capacity
DE000040	98%
DE000342	100%
DE000345	99%
DE000347	100%
DE000349	99%
DE000366	99%
DE000367	99%
DE000368	99%
DE000370	83%
DE000387	98%
DE000390	99%
DE000391	100%
DE000460	99%
DE000484	100%
DE000485	100%
DE000486	100%
DE000497	100%

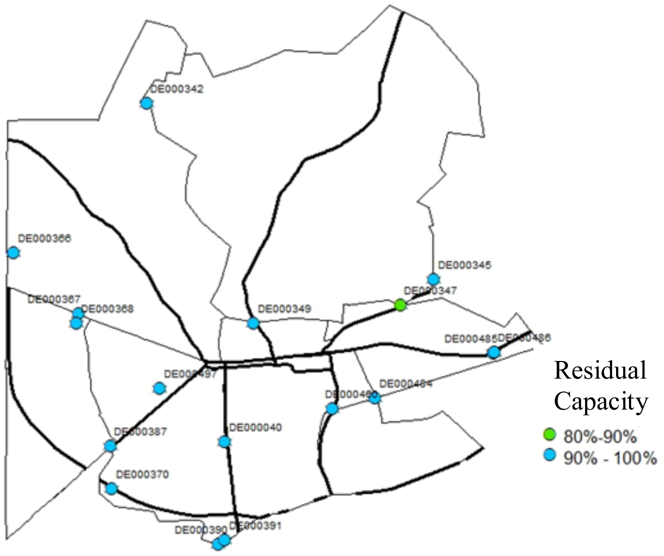


Figure 4 Residual Capacity for Bridges after a Small Earthquake

4.4.2 Demand

4.4.2.1 Fire Fighting Trips

Based on the area of buildings and the peak ground acceleration, the number of ignitions in each census track was determined using Hazus-MH. The estimated number of ignitions for each census tract is shown in Table 6. There were also the number of trips from the closest fire center to each census tract to respond to a fire; one trip for each ignition is assumed in this case.

Therefore, the major earthquake generates 10.04 trips, the moderate earthquake generates 1.79 trips and the small earthquake generates 0.65 firefighting trips across the network in the first hour after the event.

4.4.2.2 Medical Trips

Again drawing on the output from Hazus-MH, the number of level 2 and 3 casualties is shown in Table 7. One trip for each casualty was assumed from the origin census tract to the hospital. It was assumed that 30% of total trips were taken during the first hour. For medical trips, the major, medium and small earthquakes generate 144, 45, and 2 medical trips, respectively, across the network in the first hour after the event.

4.4.2.3 Search and Rescue Trips

Completely damaged buildings were considered the destination for search and rescue trips: two trips were assessed for each completely damaged concrete/steel building, while one trip was assessed for each wooden building to the network from the closest fire center. It was assumed that 15% of the damaged buildings were served during the first hour. The number of damaged buildings estimated by Hazus-MH is shown in Table 8. For search and rescue trips, the major, medium and small earthquakes generate 245, 45, and two trips across the network in the first hour after the event.

Table 6 Predicted Number of Ignitions for Each Census Tract for 3 Scenarios

Tract	TFA (sq ft)	PGA			Number of Ignitions		
		Major	Medium	Small	Major	Medium	Small
10003013610	3671.032	0.81	0.33	0.20	1.33	0.19	0.06
10003014200 (Fire Center)	2311.377	0.85	0.42	0.28	0.9	0.21	0.08
10003014300	3649.166	0.82	0.3	0.18	1.36	0.16	0.05
10003014402	2598.609	0.86	0.35	0.23	1.05	0.16	0.06
10003014403 (Fire Center)	3462.698	0.86	0.33	0.21	1.41	0.19	0.06
10003014404	2850.939	0.84	0.32	0.19	1.1	0.14	0.05
10003014501	1530.455	0.87	0.35	0.23	0.63	0.1	0.04
10003014502 (Fire Center)	3923.138	0.87	0.41	0.27	1.62	0.34	0.13
10003014703	2895.217	0.85	0.45	0.30	1.14	0.3	0.12

Table 7 Predicted Number of Casualties for Each Census Tract

Tract	Major		Medium		Small	
	Level 2 & 3 casualties	**30% for first hour**	**Level 2 & 3 casualties**	**30% for first hour**	**Level 2 & 3 casualties**	**30% for first hour**
10003013610	51	15	11	3	1	0
10003014200 (Fire Center)	58	17	25	7	2	1
10003014300	46	14	8	2	0	0
10003014402	71	21	22	7	1	0
10003014403 (Fire Center)	56	17	13	4	1	0
10003014404	29	9	6	2	0	0
10003014501	35	11	11	3	1	0
10003014502 (Fire Center)	103	31	43	13	2	1
10003014703	31	9	14	4	1	0

Table 8 Predicted Number of Damaged Buildings

Tract	Major		Medium		Small	
	Completely Damaged Buildings	15% for first hour	Completely Damaged Buildings	15% for first hour	Completely Damaged Buildings	15% for first hour
10003013610	268	40	53	8	4	1
10003014200 (Fire Center)	119	18	63	9	3	1
10003014300	253	38	39	6	3	1
10003014402	173	26	52	8	3	0
10003014403 (Fire Center)	184	28	41	6	3	0
10003014404	212	32	39	6	3	1
10003014501	57	8	25	4	1	0
10003014502 (Fire Center)	126	19	72	11	3	1
10003014703	241	36	128	19	10	2

4.4.2.4 Incremental Transportation Demand Due to Earthquake Response

Based on the estimated number of firefighting responses, the medical emergency and search and rescue trips, an origin destination matrix representing the incremental trips was generated. This matrix for the major earthquake is shown in Table 9. The entries represent the trips between the zone and the closest fire station or hospital. As the matrix shows, there were not a large number of emergency response trips. However, as these additional trips occur on a damaged network, delay was incurred. The trips in the shaded cells were those most likely to be impacted by the earthquake.

Table 9 Incremental Demand Due to Emergency Response (Trips/Hour)

	90003 (Hospital)	10003013610	10003014200 (Fire Center)	10003014300	10003014402	10003014403 (Fire Center)	10003014404	10003014501	10003014502 (Fire Center)	10003014703
10003013610	15									
10003014200 (Fire Center)	17	41.33	18.90					8.63		37.14
10003014300	14									
10003014402	21									
10003014403 (Fire Center)	17			39.36		29.41	33.10			
10003014404	9									
10003014501	11									
10003014502 (Fire Center)	31				27.05				20.62	
10003014703	9									
90003 (Hospital)	0	15	17	14	21	17	9	11	31	9

4.5 Case Study Results

For each of the three earthquake scenarios (major, moderate or small), the damaged network represented by the residual capacity of the bridges and the additional demand generated by the earthquake response was input into Cube. The existing traffic on the network was represented by 10 percent of the daily traffic to reflect the evening peak hour. This traffic served as an estimation of the trips made by individuals and this was the base traffic to which the incremental traffic was assigned.

4.5.1 Travel Times between Census Tracts

The travel times were computed using Cube and the process described in Section 3.3.4.2. Travel times between hospital and fire centers and other zones before earthquake (in minutes) are shown in Table 10. The shaded entries represent the travel time between the zone and the closest fire station or hospital. The travel times between the hospital and fire centers and other zones after the major earthquake are shown in Table 11 and the difference in travel time are shown in Table 12. Similar data for the medium and small earthquakes are shown in Table 13, Table 14, Table 15 and Table 16.

The travel delay for each of the three earthquakes is summarized in Table 17. The change was negligible for the small earthquake and modest for the medium earthquake (less than one vehicle hour). However, total delay was significant for the major earthquake. While firefighting trips experience negligible delay (7.5 vehicle minutes), both medical and search and rescue trips experience significant delays with individuals' trips increasing by as much as 4 minutes.

The number of trips made for emergency response was limited comparing to the background traffic (evening peak hour trips). So, the major impact on travel delays was due to network damage.

The network damage specifically for remote areas with limited connectivity was the greatest factor in excessive travel delay.

Table 10 Travel Times betweeen Hospitals and Fire Center and Other Zones Before an Earthquake

	90003 (Hospital)	10003013610	10003014200 (Fire Center)	10003014300	10003014402	10003014403 (Fire Center)	10003014404	10003014501	10003014502 (Fire Center)	10003014703
10003013610	7.55	0.00	5.63	7.43	8.10	7.79	8.23	6.42	5.99	7.97
10003014200 (Fire Center)	4.16	5.63	0.00	6.27	5.44	4.69	5.78	2.96	2.57	4.26
10003014300	8.78	7.43	5.57	0.00	5.97	4.22	4.38	4.99	5.33	7.52
10003014402	7.19	8.18	4.86	5.93	0.00	3.47	4.26	4.46	3.95	4.82
10003014403 (Fire Center)	7.24	7.52	4.99	4.22	3.42	0.00	1.39	3.79	3.31	5.50
10003014404	8.32	8.39	6.08	4.38	4.19	1.39	0.00	4.88	4.40	6.59
10003014501	6.71	6.93	4.42	4.99	4.18	3.43	4.51	0.00	2.49	4.98
10003014502 (Fire Center)	4.87	6.13	2.64	5.46	4.22	3.71	4.79	1.98	0.00	2.96
10003014703	3.87	7.97	4.26	7.44	4.82	5.68	6.76	3.95	3.05	0.00
90003 (Hospital)	0.00	7.55	4.16	8.69	7.23	6.93	8.02	5.20	4.81	3.91

Table 11 Travel Times between Zones after a Major Earthquake

	90003 (Hospital)	10003013610	10003014200 (Fire Center)	10003014300	10003014402	10003014403 (Fire Center)	10003014404	10003014501	10003014502 (Fire Center)	10003014703
10003013610	8.65	0.00	7.38	9.06	12.20	10.43	10.84	9.00	8.38	10.62
10003014200 (Fire Center)	4.45	8.63	0.00	8.31	8.99	6.82	7.91	4.47	4.02	5.78
10003014300	12.92	12.02	9.58	0.00	7.59	4.51	4.44	6.03	6.45	8.85
10003014402	7.22	16.62	7.78	7.71	0.00	3.70	5.01	5.86	4.85	4.83
10003014403 (Fire Center)	7.68	14.81	10.38	4.40	4.28	0.00	1.39	4.04	3.53	5.93
10003014404	8.77	15.08	11.47	4.45	5.06	1.39	0.00	5.14	4.62	7.02
10003014501	7.28	11.67	8.15	5.38	5.81	3.63	4.73	0.00	2.67	5.53
10003014502 (Fire Center)	5.06	10.57	5.86	6.50	4.76	4.42	5.51	2.07	0.00	3.07
10003014703	3.90	12.68	7.68	8.92	4.83	6.83	7.93	4.49	3.23	0.00
90003 (Hospital)	0.00	8.50	4.45	9.90	7.26	7.82	8.91	5.47	5.02	3.93

Table 12 Travel Times Difference before and after a Major Earthquake (mins)

	90003 (Hospital)	10003013610	10003014200 (Fire Center)	10003014300	10003014402	10003014403 (Fire Center)	10003014404	10003014501	10003014502 (Fire Center)	10003014703
10003013610	1.10	0.00	1.75	1.63	4.11	2.64	2.60	2.58	2.39	2.66
10003014200 (Fire Center)	0.29	3.00	0.00	2.04	3.55	2.13	2.14	1.51	1.45	1.52
10003014300	4.14	4.58	4.02	0.00	1.62	0.29	0.06	1.04	1.12	1.32
10003014402	0.03	8.44	2.92	1.78	0.00	0.23	0.75	1.40	0.91	0.01
10003014403 (Fire Center)	0.44	7.29	5.39	0.18	0.87	0.00	0.00	0.25	0.22	0.43
10003014404	0.45	6.69	5.39	0.07	0.88	0.00	0.00	0.26	0.22	0.43
10003014501	0.57	4.74	3.73	0.39	1.63	0.20	0.22	0.00	0.18	0.55
10003014502 (Fire Center)	0.19	4.44	3.22	1.04	0.55	0.72	0.73	0.09	0.00	0.12
10003014703	0.03	4.71	3.42	1.47	0.01	1.15	1.17	0.54	0.18	0.00
90003 (Hospital)	0.00	0.94	0.29	1.20	0.03	0.89	0.89	0.27	0.21	0.02

Table 13 Travel Time between Zones after a Medium Earthquake (mins)

	90003 (Hospital)	10003013610	10003014200 (Fire Center)	10003014300	10003014402	10003014403 (Fire Center)	10003014404	10003014501	10003014502 (Fire Center)	10003014703
10003013610	8.45	0.00	6.86	8.12	10.27	9.27	9.70	7.88	7.36	9.12
10003014200 (Fire Center)	4.40	6.57	0.00	7.28	6.90	5.91	7.01	3.57	3.08	4.44
10003014300	10.18	8.29	6.97	0.00	7.30	4.32	4.44	6.00	5.98	8.38
10003014402	7.22	10.28	5.57	7.39	0.00	3.70	4.56	5.52	4.48	4.83
10003014403 (Fire Center)	7.88	9.02	5.93	4.31	3.74	0.00	1.39	4.20	3.68	6.08
10003014404	8.98	9.82	7.02	4.45	4.58	1.39	0.00	5.29	4.78	7.17
10003014501	7.33	8.30	5.37	5.38	5.40	3.73	4.83	0.00	2.67	5.53
10003014502 (Fire Center)	5.11	7.40	3.14	6.13	4.65	4.42	5.52	2.07	0.00	3.08
10003014703	3.90	8.88	4.43	8.19	4.83	6.72	7.82	4.27	3.23	0.00
90003 (Hospital)	0.00	8.32	4.41	9.45	7.26	7.98	9.08	5.53	5.08	3.93

Table 14 Travel Time Difference Before and After a Medium Earthquake (mins)

	90003 (Hospital)	10003013610	10003014200 (Fire Center)	10003014300	10003014402	10003014403 (Fire Center)	10003014404	10003014501	10003014502 (Fire Center)	10003014703	
10003013610	0.90	0.00	1.23	0.68	2.17	1.48	1.47	1.46	1.38	1.15	0.90
10003014200 (Fire Center)	0.24	0.94	0.00	1.01	1.45	1.23	1.24	0.61	0.51	0.18	0.24
10003014300	1.40	0.86	1.41	0.00	1.33	0.10	0.06	1.01	0.65	0.86	1.40
10003014402	0.03	2.09	0.71	1.46	0.00	0.23	0.30	1.07	0.53	0.01	0.03
10003014403 (Fire Center)	0.64	1.50	0.94	0.09	0.32	0.00	0.00	0.41	0.37	0.58	0.64
10003014404	0.66	1.43	0.95	0.07	0.40	0.00	0.00	0.41	0.38	0.58	0.66
10003014501	0.62	1.37	0.95	0.39	1.22	0.30	0.32	0.00	0.18	0.55	0.62
10003014502 (Fire Center)	0.24	1.27	0.50	0.67	0.43	0.72	0.73	0.09	0.00	0.12	0.24
10003014703	0.03	0.92	0.17	0.75	0.01	1.04	1.06	0.32	0.18	0.00	0.03
90003 (Hospital)	0.00	0.77	0.25	0.76	0.03	1.05	1.06	0.33	0.28	0.02	0.00

Table 15 Travel Time between Hospital and Fire Center and Other Zones after a Small Earthquake (mins)

	90003 (Hospital)	10003013610	10003014200 (Fire Center)	10003014300	10003014402	10003014403 (Fire Center)	10003014404	10003014501	10003014502 (Fire Center)	10003014703
10003013610	7.55	0.00	5.63	7.43	8.10	7.79	8.23	6.42	5.99	7.97
10003014200 (Fire Center)	4.16	5.63	0.00	6.27	5.44	4.69	5.78	2.96	2.57	4.26
10003014300	8.78	7.43	5.57	0.00	5.97	4.22	4.38	4.99	5.33	7.52
10003014402	7.19	8.18	4.86	5.93	0.00	3.47	4.26	4.46	3.95	4.82
10003014403 (Fire Center)	7.24	7.52	4.99	4.22	3.42	0.00	1.39	3.79	3.31	5.50
10003014404	8.32	8.39	6.08	4.38	4.19	1.39	0.00	4.88	4.40	6.59
10003014501	6.71	6.93	4.42	4.99	4.18	3.43	4.51	0.00	2.49	4.98
10003014502 (Fire Center)	4.87	6.13	2.64	5.46	4.22	3.71	4.79	1.98	0.00	2.96
10003014703	3.87	7.97	4.26	7.44	4.82	5.68	6.76	3.95	3.05	0.00
90003 (Hospital)	0.00	7.55	4.16	8.69	7.23	6.93	8.02	5.20	4.81	3.91

Table 16 Travel Time Difference before and after a Small Earthquake (mins)

	90003 (Hospital)	10003013610	10003014200 (Fire Center)	10003014300	10003014402	10003014403 (Fire Center)	10003014404	10003014501	10003014502 (Fire Center)	10003014703
10003013610	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10003014200 (Fire Center)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10003014300	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10003014402	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10003014403 (Fire Center)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.00
10003014404	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10003014501	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10003014502 (Fire Center)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10003014703	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
90003 (Hospital)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 17 Travel Delay for First Hour by Source (Vehicle-Minutes)

Earthquake	Medical Trips	Fire Fighting Trips	Search and Rescue Trips	Total Delay (TD)
Major	173.21	7.49	207.78	388.49
Medium	33.12	0.37	17.31	50.81
Small	0	0	0	0

4.5.2 Other Performance Index

The Disruption Index (DI) and Revised Disruption Index (RDI) are also calculated and are shown in Table 18. The measures behave as expected but do not provide a lot of additional insight as the network was relatively resilient.

Table 18 Performance Measures for Newark Case Study

Scenario	Disruption Index (DI)	Revised Disruption Index (RDI)
Major Earthquake	1.102	1.268
Medium Earthquake	1.052	1.169
Minor Earthquake	1.000	1.000

4.6 Conclusions

The analysis showed the network resilience in Newark responding to small and medium earthquake. The travel delay (changes in travel time times by emergency response trips) for trips between zones was negligible for medium and small earthquake. However, for the major earthquake, the total delay experienced by emergency responders was significant. The most problematic area was zone 10003014300, in which the trip from the closest fire center represents one of the longest without network damage. This zone was also in a vulnerable condition due to overall greatest increase in travel time after both the major and medium earthquake scenarios. For the major earthquake, the response time for medical trips was 1.5 times that of the response time in normal condition. This zone's vulnerability also increases due to the fact it is one of the largest and most remote zones within city limits.

Small changes in travel time for small and medium earthquakes arise because the number of bridges in the city is limited. Moreover, because of low volume traffic, the network was not congested even at peak hour, adding limited numbers of emergency response trips to the uncongested network did not cause critical delays.

However, for the major earthquake, the analysis provided some insight into where resources might be placed to better respond to events and potentially identified critical links, such as bridges, that can impede the movement of emergency vehicles. The most affected zone (identified) shows that the problem lied in the distance between this zone and closest medical center and lack of alternatives.

This case study facilitated exploration of the issues and testing of the software using a familiar network. To better understand the implications of this type of analysis, this analysis was repeated for a more congested and earthquake-prone area – the San Fernando Valley. This case study is presented in the next chapter.

Chapter 5

CASE STUDY: SAN FERNANDO VALLEY

5.1 Introduction

The purpose of this research is to understand the transportation system dynamics immediately after an earthquake, estimate the possible delays for emergency response operations that occur after a disaster, and explore opportunities for mitigating the disaster impact or improving preparedness. In the previous chapter, the method was explained by applying it to a small network using hypothetical scenarios.

In this chapter, a more complicated network with realistic scenarios is analyzed. The area chosen for this case study had four important features:

1. It was located in an earthquake prone area
2. It covered a populated area served by a congested network
3. The damage resulting from earthquake events required significant numbers of emergency response trips following the earthquake event
4. A relatively recent earthquake occurred in this area provided some data for validation.

All these features exist in the San Fernando Valley, California, which is located in Los Angeles County, California, northwest of the city of Los Angeles. Furthermore, the San Fernando Valley, which was severely impacted by the Northridge earthquake in 1994, is surrounded by mountains and is connected to neighboring communities by a limited number of links. The relative remoteness of this area makes it an appropriate study area, since the external trips can easily be controlled and the assumption that the emergency response trips are internal to the area, specifically for the first hour after event, was realistic. Moreover, three major highways (I-5 and I-405 and state route 101) are located in this area, which makes it a good candidate to explore the impact of the earthquake on corridors.

The methodology used to develop this case study is the same methodology described in Chapter 3 and Chapter 4 for the city of Newark case study. The one significant difference between this chapter and Chapter 4 is that the earthquake scenarios used to represent the hazards are realistic for this area. The probabilistic method using representative scenarios is described in the next section. The following section describes the case study area and data used for the analysis. The section after presents the travel times between census tracts and then the performance measures. A concluding section summarizes the results.

5.2 Representative Earthquake Scenarios and Review of the Methodology

In this case study, the representative scenarios determined in Chang et al.'s paper (2000) were used. The probabilistic method was used to determine 47 earthquake scenarios for Los Angeles and Orange counties. These 47 scenarios were designed to be representative of all possible historical and earthquake scenarios for these two counties. Hazard consistent probabilities were assigned to these representative scenarios in a way that these representative scenarios will have the same effect on the network as the whole database of earthquakes identified by the United States Geological Survey. The list of earthquake scenarios used in this research is shown in Table 19.

Similar to the Newark case study, the reduction in the capacity of the transportation network and the trips generated to transfer the injured to medical services, for firefighting and for search and rescue, were estimated. Then, the performance measures, such as total delay and damage index, were calculated.

Table 19 The 47 Representative Earthquake Scenarios

Scenario	Magnitude	Fault	Type[1]	Latitude	Longitude
1	7.1	Elysian Park	MCE	-	-
2	7.3	Malibu Coast	MCE	-	-
3	7	Newport-Inglewood (N)	MCE	-	-
4	7	Newport-Inglewood (S)	MCE	-	-
5	7.2	Palos Verdes	MCE	-	-
6	6.7	Raymond	MCE	-	-
7	8	San Andreas	MCE	-	-
8	7.5	Sn Jacinto	MCE	-	-
9	6.9	Santa Susana	MCE	-	-
10	7.4	Sierra Madre	MCE	-	-
11	7.5	Simi Santa Rosa	MCE	-	-
12	6.8	Verdugo	MCE	-	-
13	7.5	Whittier	MCE	-	-
14	6	Malibu Coast	U/D	34.1395	-118.042
15	6	Malibu Coast	U/D	34.1161	-118.158
16	6	Malibu Coast	U/D	34.0944	-118.372
17	6	Newport-Inglewood	U/D	33.8961	-118.269
18	6	Newport-Inglewood	U/D	33.0079	-118.374
19	6	Newport-Inglewood	U/D	33.8168	-118.197
20	6	Newport-Inglewood	U/D	33.7369	-118.079
21	6	Newport-Inglewood	U/D	33.6448	-117.955
22	6	Palos Verdes	U/D	33.7782	-118.315
23	6	San Andreas	U/D	34.4306	-117.815
24	6	San Andreas	U/D	34.6266	-118.319
25	6	San Jacinto	U/D	34.2631	-117.499
26	6	Santa Susana	U/D	34.3279	-118.607
27	6	San Fernando	U/D	34.2937	-118.468
28	6	Sierra Madre	U/D	34.2559	-118.254
29	6	Sierra Madre	U/D	34.1605	-117.92
30	6	Whittier	U/D	33.9571	-117.907
31	6.5	Malibu Coast	U/D	34.1431	-118.122
32	6.5	Malibu Coast	U/D	34.1092	-118.073
33	6.5	Malibu Coast	U/D	34.0916	-118.38
34	6.5	Newport-Inglewood	U/D	33.9399	-118.319
35	6.5	Newport-Inglewood	U/D	33.7901	-118.146
36	6.5	Newport-Inglewood	U/D	33.6557	-118.959
37	6.5	San Andreas	U/D	34.5936	-118.205
38	6.5	San Andreas	U/D	34.4388	-117.839
39	6.5	San Jacinto	U/D	34.2301	-117.454
40	6.5	San Fernando	U/D	34.2966	-118.423
41	6.5	Whittier	U/D	33.9242	-117.841
42	7	Malibu Coast	U/D	34.0652	-118.456
43	7	Malibu Coast	U/D	34.1232	-118.157
44	7	San Jacinto	U/D	34.2372	-117.463
45	7	San Andreas	U/D	34.5726	-118.179
46	7	San Andreas	U/D	34.4032	-117.732
47	7	Whittier	U/D	33.9401	-117.884

1) MCE = Maximum credible earthquake; U/D =User-defined event

5.3 Overview of the Case Study and Data

This case study evaluates the transportation network performance after an earthquake in the San Fernando Valley, a heavily populated area in the northwest part of Los Angeles County. The area has a population around 1.8 million and covers about 670 square kilometers. Figure 5 shows the geographic location of the study area.

The following data were used for the case study:

- Forty seven (47) representative earthquake scenarios as shown in Table 19 range in magnitude from 6 to 8.
- Twenty (20) hospitals (Healthcare Atlas) and twenty-eight (28) fire centers (LAFD) were considered as the trip generation/attraction points for emergency response trips. Figure 6 shows the location of hospitals and fire centers in San Fernando Valley.
- Transportation network model for the San Fernando Valley defining the links, connectivity and location of the trip generation and attraction points. The network was obtained from SCAG (Southern California Association of Governments) and is the network SCAG uses for transportation planning. The network was for the whole LA County and was modeled as 4,192 zones and 266,748 links. The number of zones that was actually located in the study area is 344.
- Bridge data for bridges in the study area were extracted from NBI (National Bridge Inventory) database. There were 460 bridges in the study area. The network and bridges in the study area is shown in Figure 7.

Figure 5 Geographic Location of the Study Area

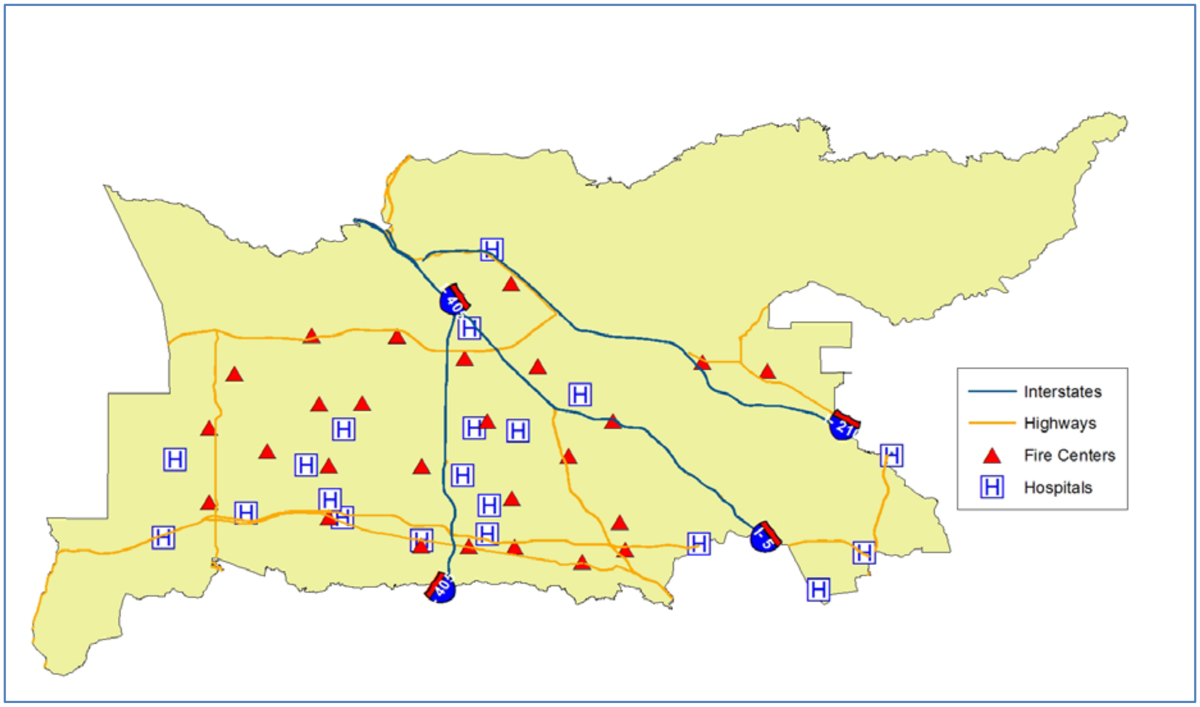


Figure 6 Locations of Hospitals and Fire Centers

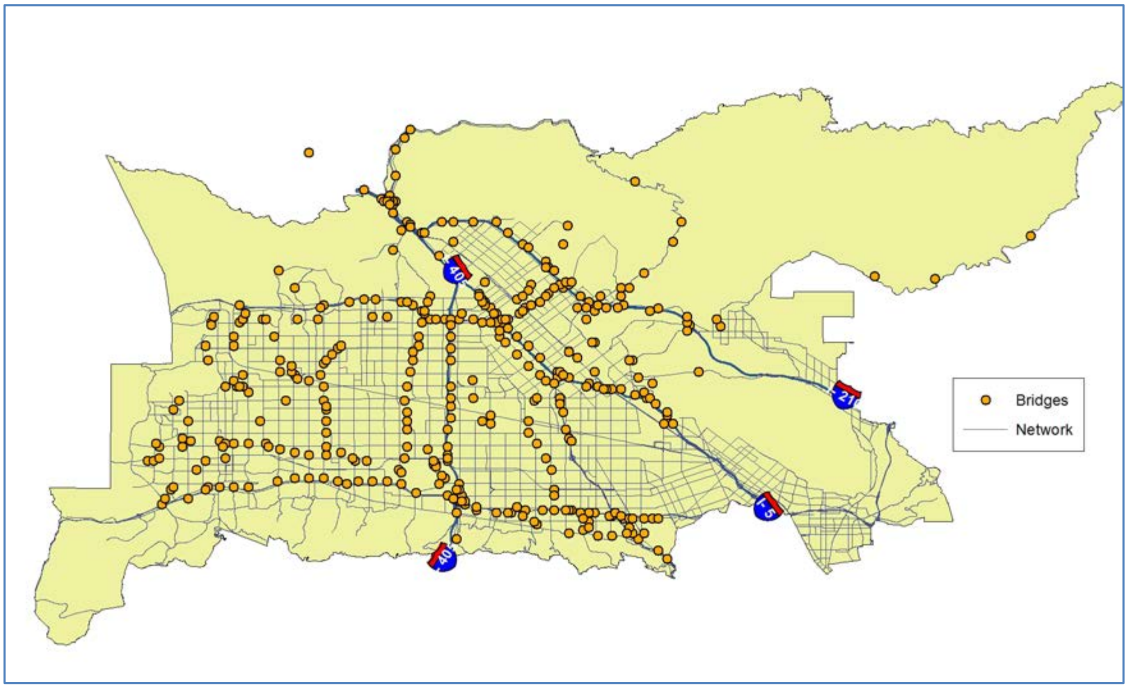


Figure 7 Road Network and Bridges in the San Fernando Valley Study Area

The regular peak hour travel time and traffic were considered as the base network load (Lamb & Walton, 2011), the emergency response trips from/to attraction points to/from all census tracts are added to the network, and the difference between travel time for the undisrupted and damaged network for emergency response trips was calculated. Travel delay as an indication of the network performance is also estimated.

5.4 Travel Times between Census Tracts

The travel times between the hospital and fire centers and other zones for the undisrupted network and the damaged network were calculated for each of the 47 earthquake scenarios. Given the number of scenarios, origins, and destinations of interest, and links in the network, visually examining the tables of travel times did not immediately provide any insight. Therefore, we develop a strategy to identify problematic times and zones in terms of the impact of an earthquake scenario on the travel times of emergency response trips.

The greatest difference between travel times for all zones before and after the earthquake for each of the 47 scenarios was determined and shown in Table 20.

Table 20 Maximum Differences in Travel Time for each Earthquake Scenario (mins)

Scenario	Δt (mins)	Scenario	Δt (mins)	Scenario	Δt (mins)
S1	0.01	S17	0.02	S33	0
S2	9.85	S18	0.1	S34	10.02
S3	10.99	S19	1.35	S35	3.76
S4	10.96	S20	0.53	S36	29.78
S5	5.97	S21	5.87	S37	0.02
S6	0.94	S22	0.02	S38	11.09
S7	0.28	S23	1.92	S39	9.96
S8	15.79	S24	0	S40	38.54
S9	0.09	S25	0.01	S41	0.34
S10	2.07	S26	0.02	S42	0.07
S11	4.66	S27	0.12	S43	0.01
S12	0.13	S28	0.02	S44	0.1
S13	0.01	S29	6.9	S45	0.47
S14	0.04	S30	42.58	S46	0.12
S15	0.01	S31	0.01	S47	0.58
S16	0.22	S32	0.01		

Of the 47 scenarios, eight scenarios had a maximum difference in travel time of more than 10 minutes as shown in Table 20. Our focus was on these eight scenarios. We looked at these eight scenarios in order of descending difference in travel time: S30, S40, S36, S8, S38, S3, S4, and S34.

The frequency (number of zones) of difference in travel time before and after earthquake (delay) for the medical round trips for scenarios 30, 40, 36, and 8 is shown in Figure 8-Figure 11 respectively. Only delay greater than 1 minute is shown in these graphs.

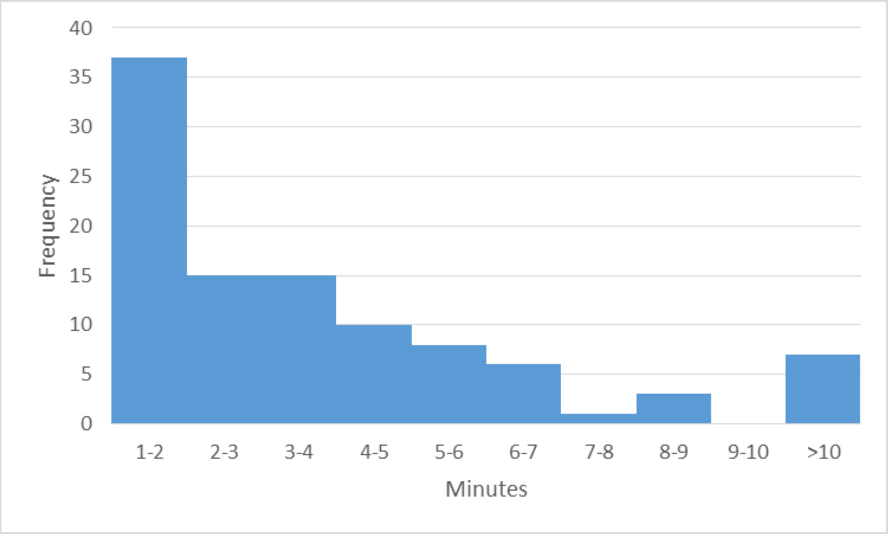


Figure 8 Frequency of Delay for Scenario 30

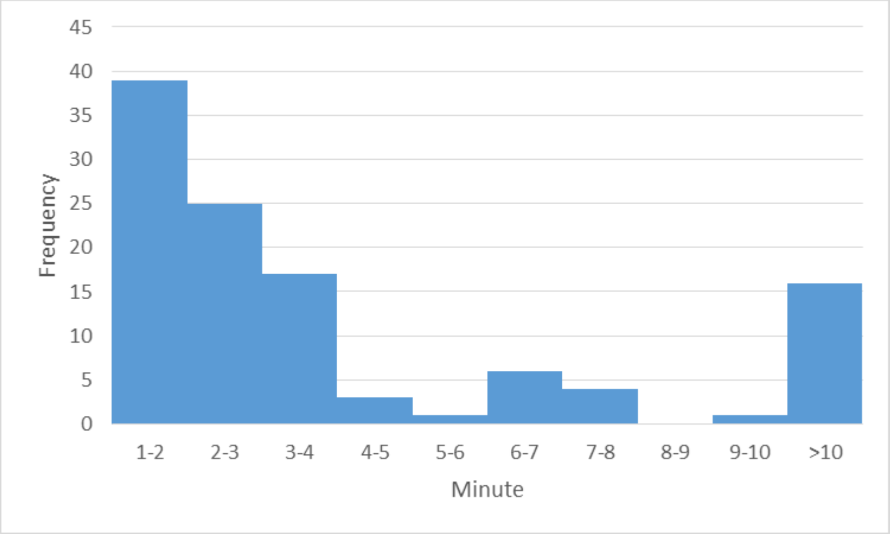


Figure 9 Frequency of Delay for Scenario 40

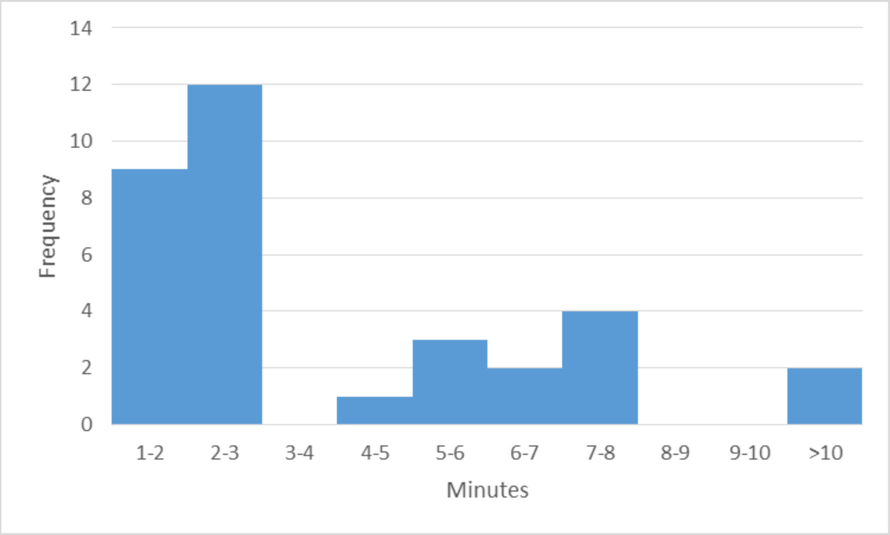


Figure 10 Frequency of Delay for Scenario 36

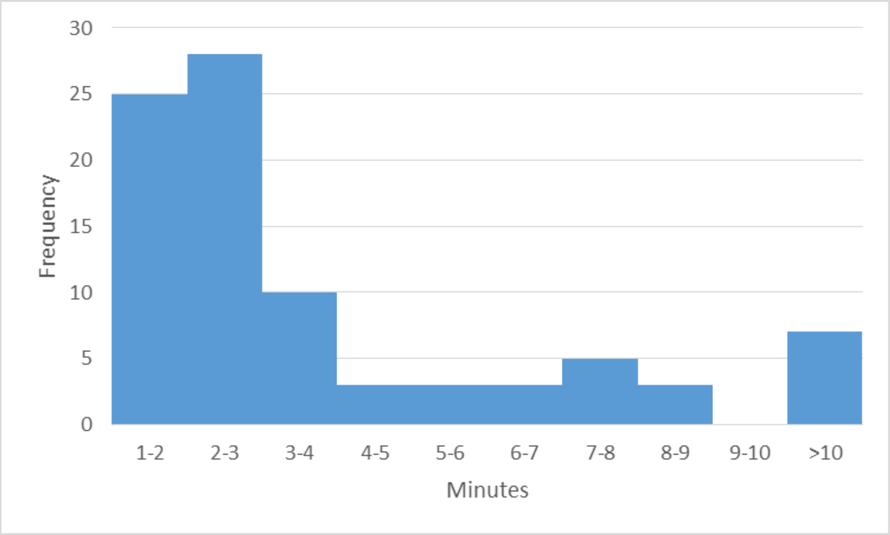


Figure 11 Frequency of Delay for Scenario 8

For each scenario, we mapped the difference in travel time for medical trips using colors and fire trips using hatching. For example, scenario S30 has the greatest difference of 42.58 (minutes). Figure 8 is a thematic map showing the marginal travel time (difference between before and after earthquake travel time) for all zones for scenario S30. Medical trips were based on the roundtrip marginal travel time from and to the closest hospital and were represented by different colors. Fire trips were based on the marginal travel time from closest fire center and were represented by different patterns. For example, Figure 8 shows a large region in the northeastern part of the San Fernando Valley, shaded red and cross-hatched in a grid pattern, indicating that medical trips are delayed more than 30 minutes (red) and trips responding from the fire station are delayed more than 10 minutes (grid pattern). This is because this area is in a mountainous region, with few alternative routes, and is the most severely impacted by the earthquake.

Figure 9 shows the same situation for scenario S40, which has the second highest difference in travel time. The following figures shows scenarios S36 (Figure 10), S8 (Figure 11), S38 (Figure 12), S3 (Figure 13), S4 (Figure 14), and S34 (Figure 15).

Table 21 shows the number of the TAZs with travel time delays greater than three minutes for travel from the closest fire center and greater than five minutes for roundtrip medical trips for the eight scenarios (S40, S30, S36, S8, S38, S3, S4, and S34). Table 21 is color coded to indicate the TAZs with the most significant delays (red indicating medical trips experiencing delays longer than 30 minutes, and fire trips longer than 10 minutes), moderate delays (orange indicating medical trips experiencing delays between 10 and 30 minutes, and fire trips experiencing delays between 5 and 10 minutes), and minor delays (green indicating medical trips experiencing delays between 5 and 10 minutes, and fire trips experiencing delays between 3 and 5 minutes). Table 22 shows the frequency of appearance of each TAZ in Table 21. Figure 16 shows the location of the TAZs that appeared most frequently in these eight scenarios on the map. This shows that the most problematic area is in northeast, which includes zones 395, 721, 725, 724, 722, and 726. Other zones with greater delays were also noticed in the south and center. The reason for the increase in delay for each zone is discussed below. In general, we reviewed the zones in descending order of the frequency with which the zones appear among the 16 scenarios (eight earthquake scenarios each with travel delay increases for medical trips and trips from fire centers) with the worst maximum delay. Where the reason for the delay is consistent among zones, we group those zones together.

- Zone 395: This zone was the most remote and most of the area is covered by forest. There were only two possible paths from the closest fire center and hospital to this area. The shortest path to the closest hospital before the earthquake takes 33 minutes during the afternoon peak hour. There were four bridges on the longest link of the path for which the capacity is reduced to 60-75% of the before earthquake capacity. Because there was no good alternative for this road the travel time after the earthquake increases greatly. The suggestions for controlling this delay are:
    - Retrofitting the bridges on the critical link, so that the capacity after the earthquake does not reduce that much.
    - Providing alternative roads. This is challenging because of environmental issues related to destroying the forest and the high cost of building roads through rugged terrain.
- Zone 721: This was a neighboring zone to zone 395. A critical link on the shortest path fails in most scenarios studied. The travel times for the second shortest path were greater than the first path. Although there is an interstate

highway adjacent to the zone, the limited access makes that route useless for emergency response vehicles. The suggestions for controlling the delay for this zone are:

  - Retrofitting the critical bridge on the shortest path
  - Providing access to the highway
  - Providing an alternate road just for the critical link.

- Zone 445: This zone was located in the downtown area of Northridge with only several alternative paths. One bridge on the shortest path failed in almost all scenarios, therefore retrofitting that single bridge was the most effective mitigation treatment that can be suggested. The alternative paths are not very helpful due to the volume of traffic on all links in the downtown area at peak hours, which cause a greater delay for the second shortest path.
- Zone 597: This zone was in a very busy area. The closest fire center is only 0.5 miles away from the center of the zone and one link connected these two nodes. The peak hour volume for this link is 2,095 vehicles/hour while the capacity of the link is 795 vehicles/hour. An earthquake causes damage to the bridge on this link in most scenarios, so once again, the only suggestion would be retrofitting that bridge. An alternate path does not work because of traffic volume and excessive delay on all links, any other path would be longer and encounter more delay,
- Zones 609, 611, 622, 603, and 626: These zones were all located in the southern suburb of Northridge close to the mountains. The area was less populated than the downtown. The closest medical center was about 8 miles from these zones and the access to that was very limited in the peak hour

period. It takes 72, 91,116, 63, and 85 minutes to reach to the nearest medical center from zone 609, 611, 622, 603, and 622 respectively. Consequently, the post-earthquake delay for this path was large and only increases. The best recommendation to control the delay for these zones was to encourage the establishment of additional medical centers in that area.

- Zones 722,724, 725, and 726: These three zones were located adjacent to zone 721, which was vulnerable in many scenarios, based on the findings. A significant part of the delay that occurred on the paths to these zones from medical/fire centers is due to the failure of the same bridge that was discussed for zone 721. These zones have an advantage over zone 721 as they had better access to the interstate highway. This access serves as the alternative path that helps to control the delay for zone 722, 724, 725, and, in some scenarios, 726. The most problematic scenarios were those with the failure of bridges on the interstate highway in addition to the critical bridge discussed. First, this reinforces the value of the suggestion to retrofit the critical bridge discussed for zone 721. The other possible solution is to consider providing emergency medical centers close to this area.
- Zones 458 and 465: these two zones were located in the downtown area near zone 445 and have a similar problem: the closest path from the fire center to both these two zones passes a bridge that failed in four out of eight scenarios. Considering the congested state of alternative paths, the best recommendation is retrofitting the bridge on the shortest path for both these zones.
- Zone 574: the biggest delay occurred for medical trips under one scenario. The delays for fire center trips are minor. One bridge was involved and this bridge

was on a long direct link to the medical center. Therefore, the bridge on this link is critical for this zone, and retrofitting the bridge is recommended.

In summary, there are two general areas northeast and south that are experiencing increases in delays in four or more scenarios. For the zones in the northeast, retrofitting critical bridges, alternative roads and additional medical centers were recommended. Because of the low population density and lack of alternative routes, providing retrofitting bridges, and providing alternative routes were more rational. For zones in the south region, pre-earthquake, congested travel times to the closest medical centers were already overwhelming, therefore providing medical centers is recommended. There were a few zones in the more connected areas for which one specific bridge plays a vital role. Retrofitting these bridges was recommended.

Furthermore, this analysis is based on the threshold maximum delay of 10 minutes. Exploring alternative thresholds (for example, 5 minutes or 15 minutes) or alternative measures such as average delay would also be worthwhile but the approach and types of conclusions are expected to be much the same.

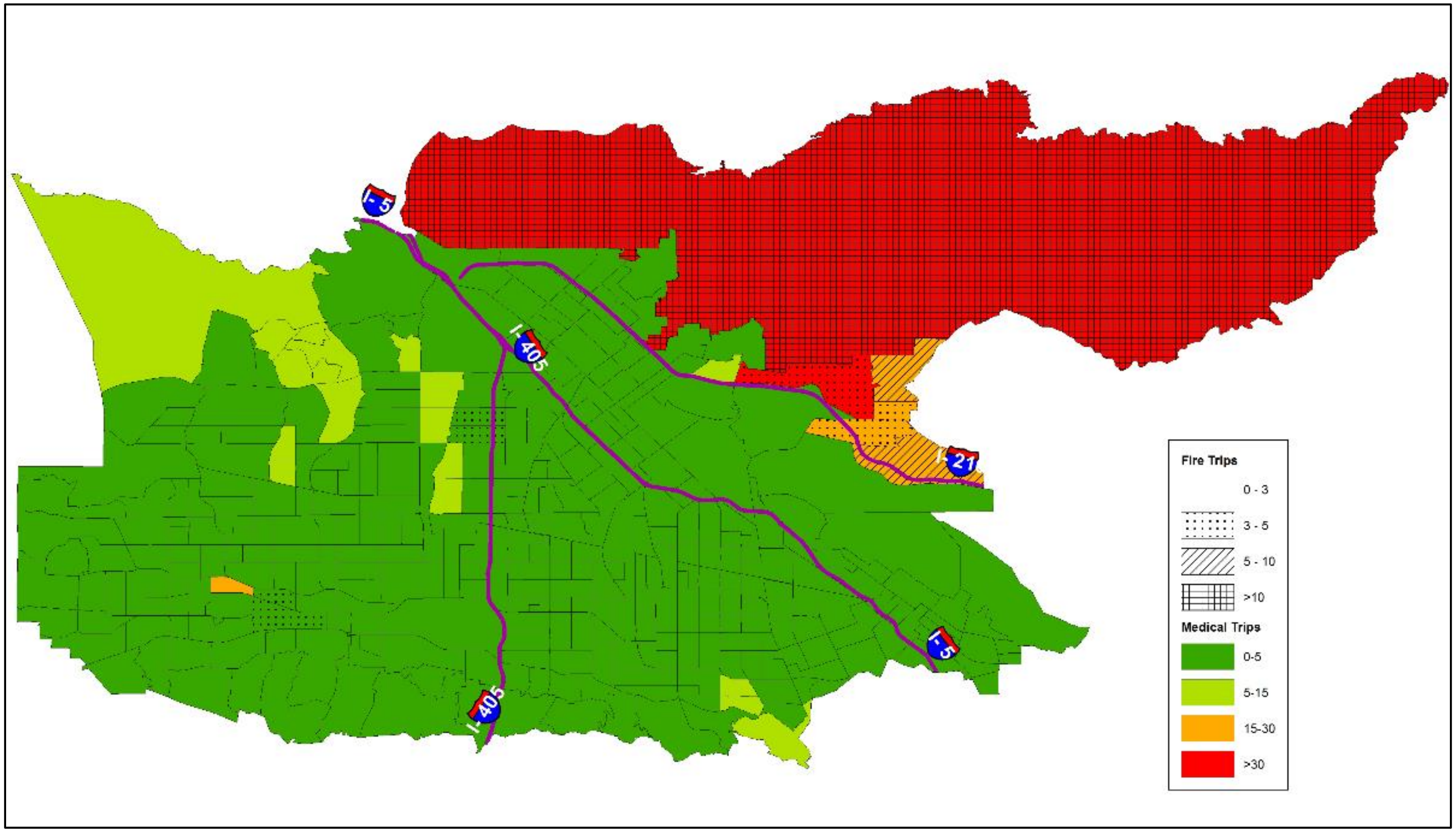


Figure 12 Differences in Travel Time for Medical and Fire Trips for Scenario S30

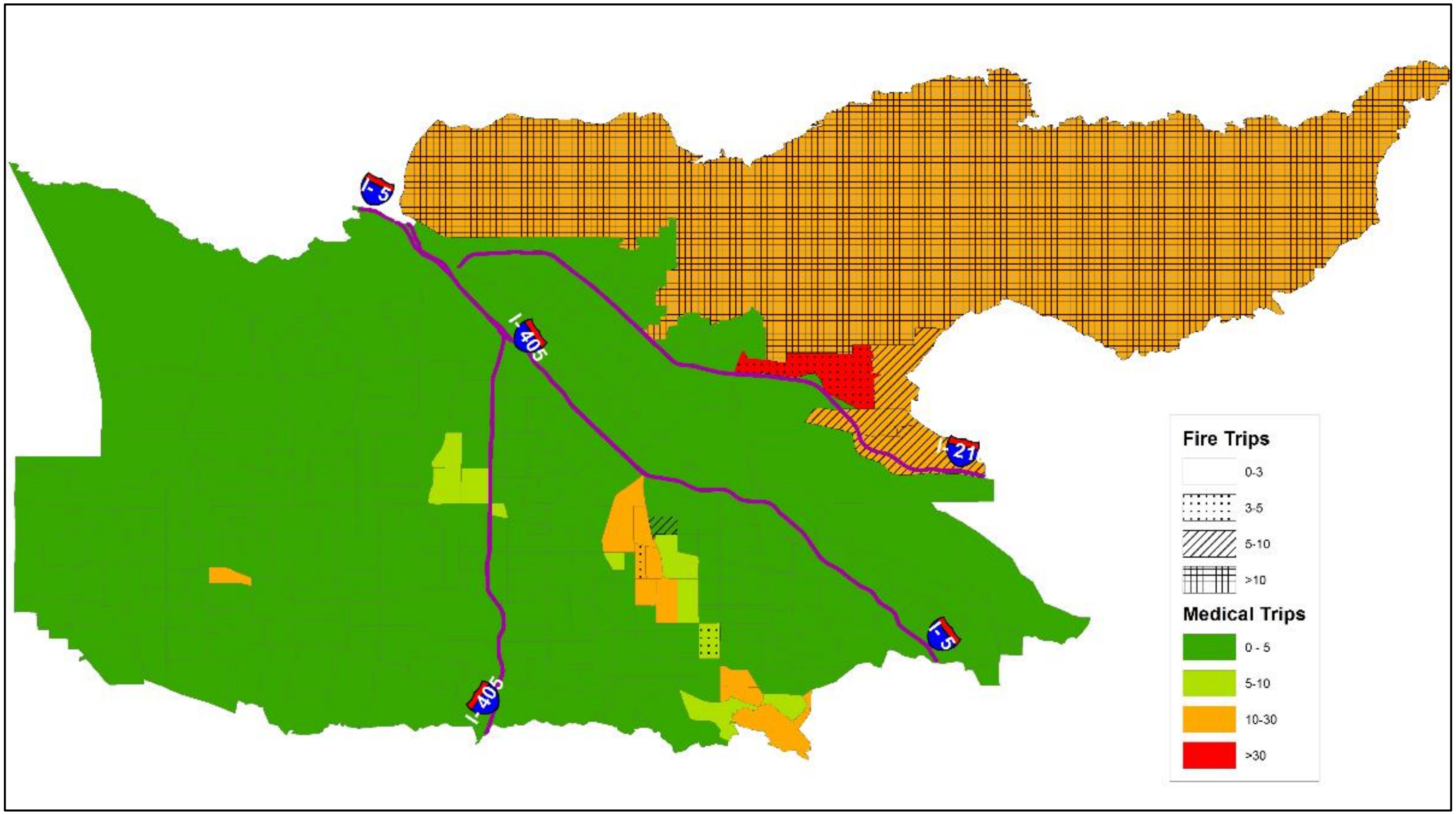


Figure 13 Differences in Travel Time for Medical and Fire Trips for Scenario S40

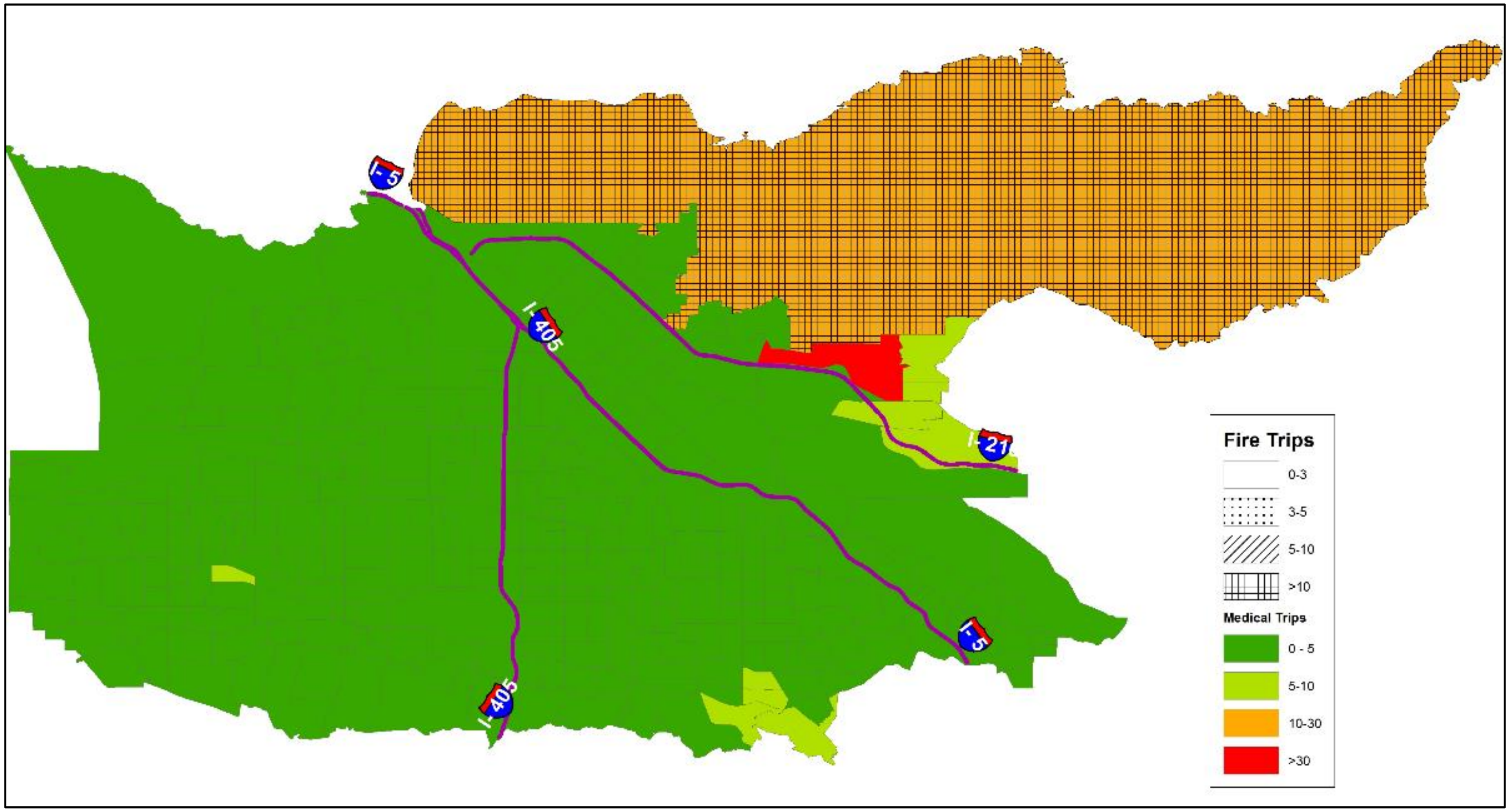


Figure 14 Differences in Travel Time for Medical and Fire Trips for Scenario 36

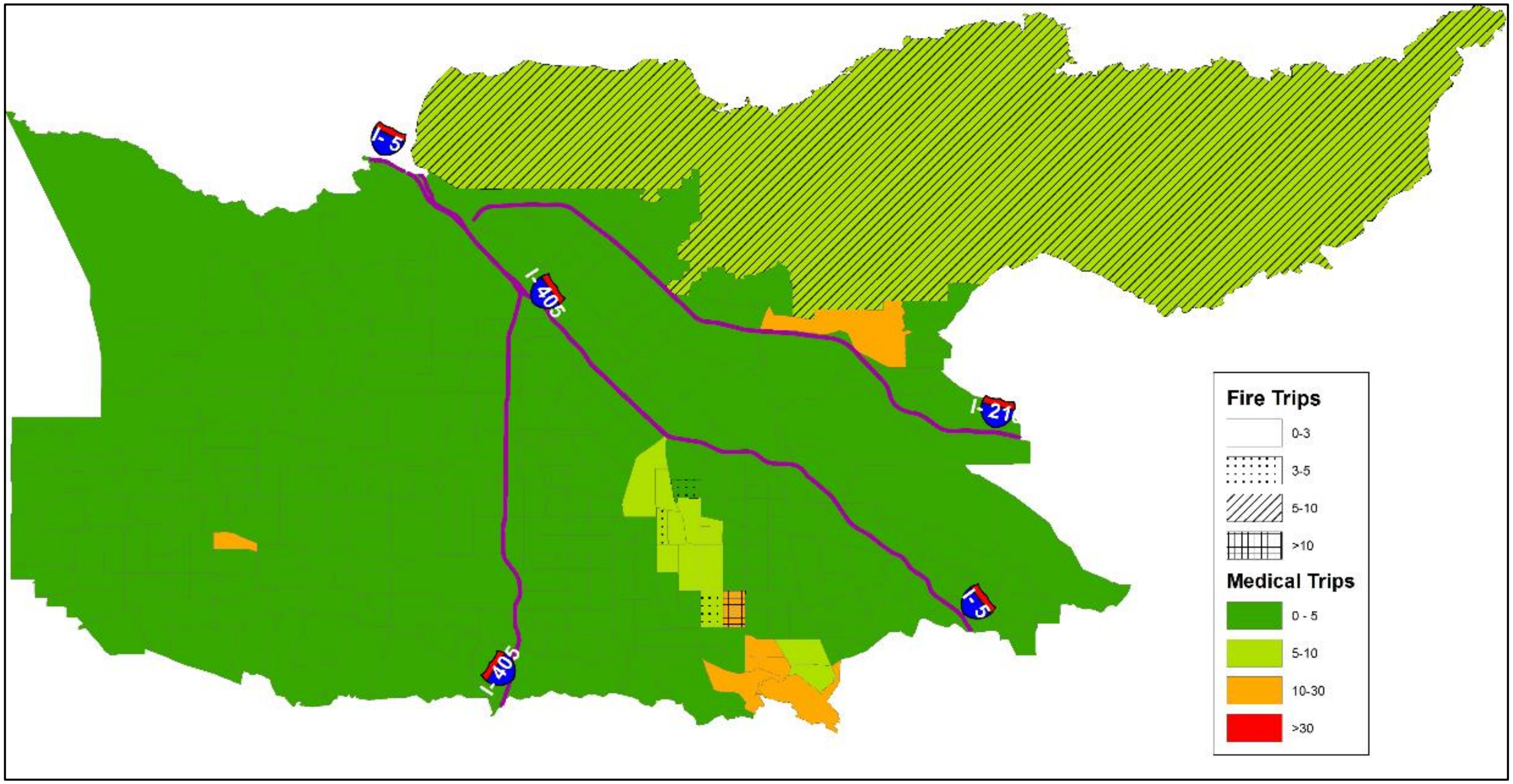


Figure 15 Differences in Travel Time for Medical and Fire Trips for Scenario S8

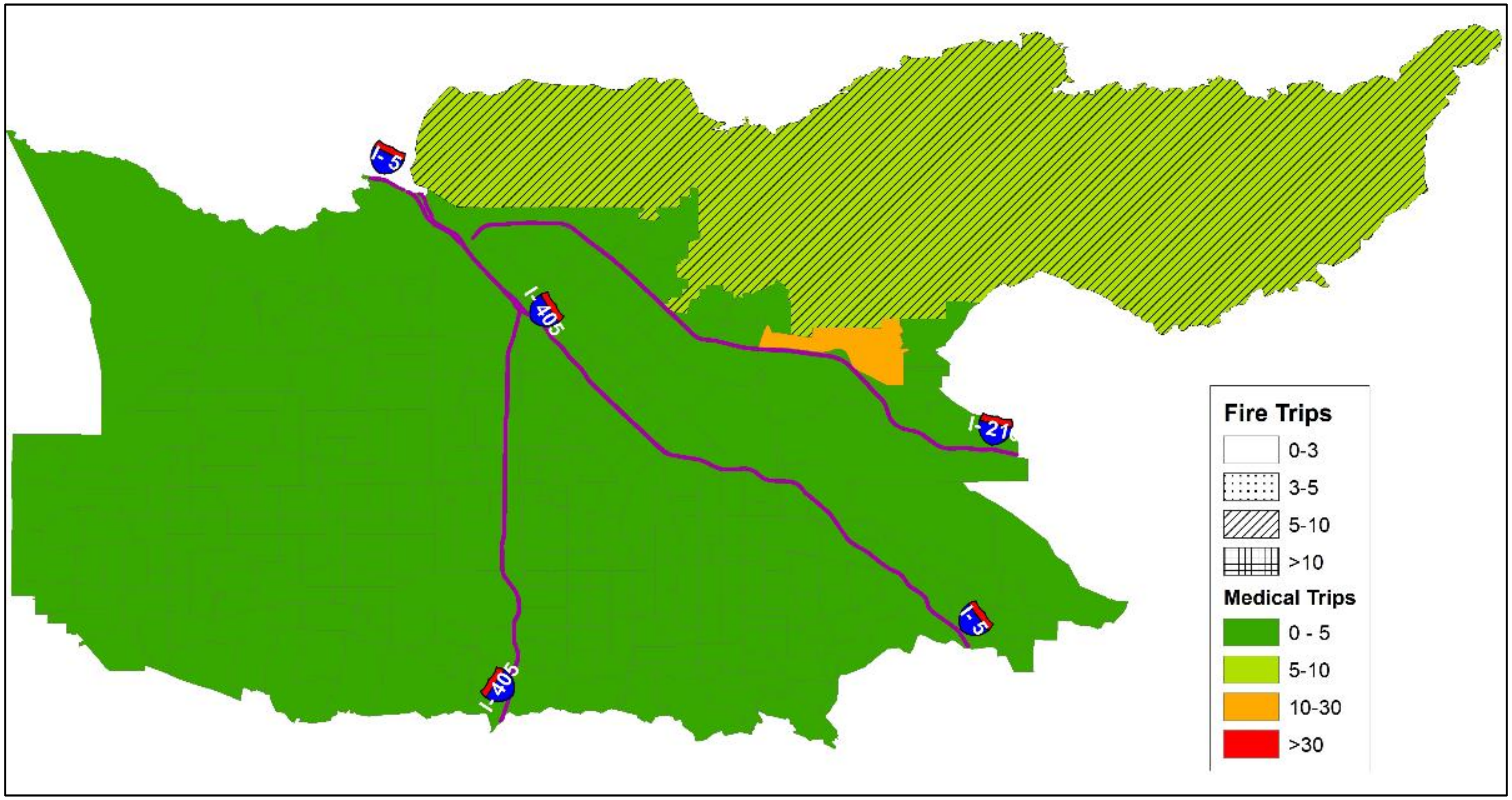


Figure 16 Differences in Travel Time for Medical and Fire Trips for Scenario 38

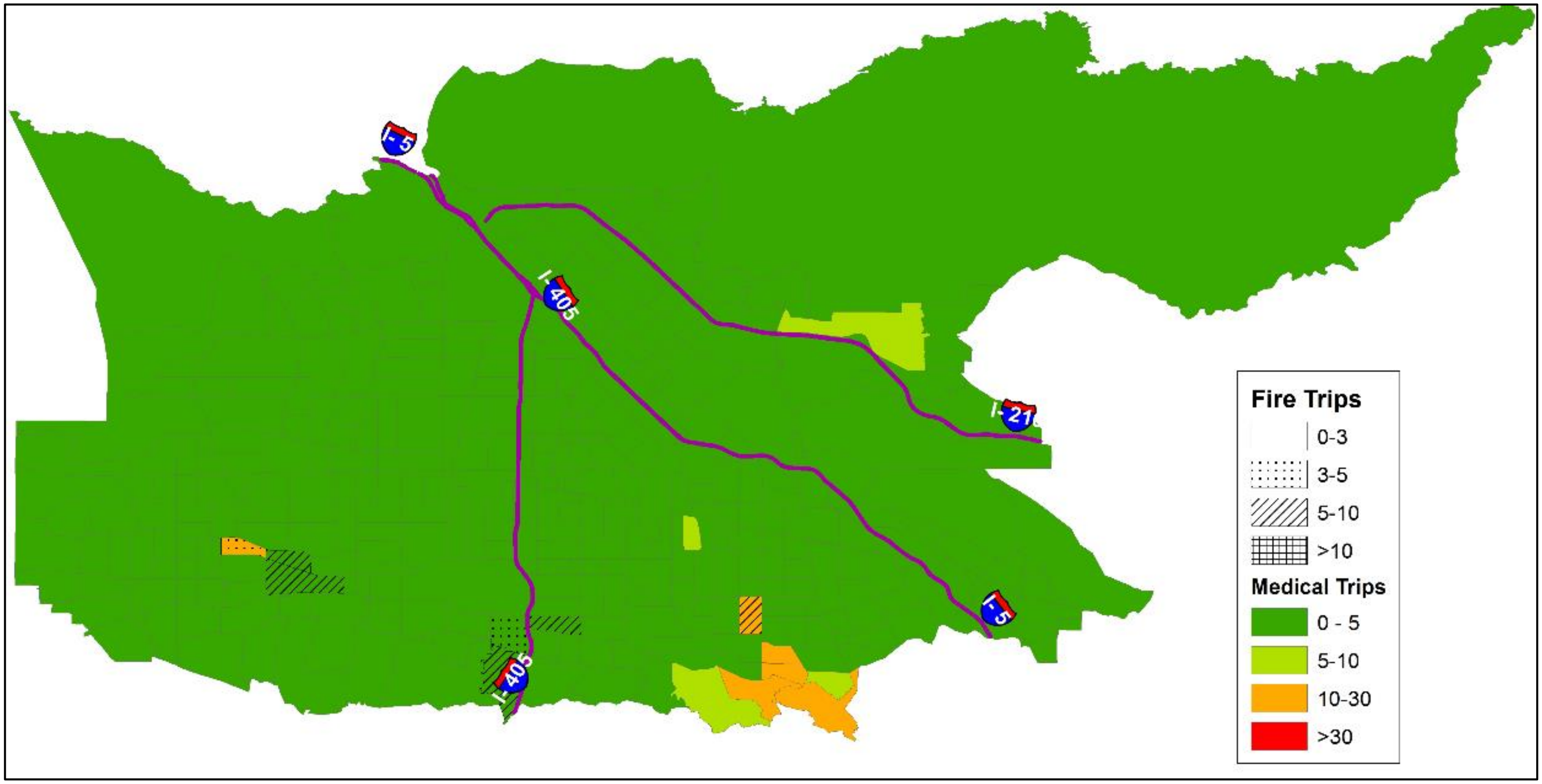


Figure 17 Differences in Travel Time for Medical and Fire Trips for Scenario S3

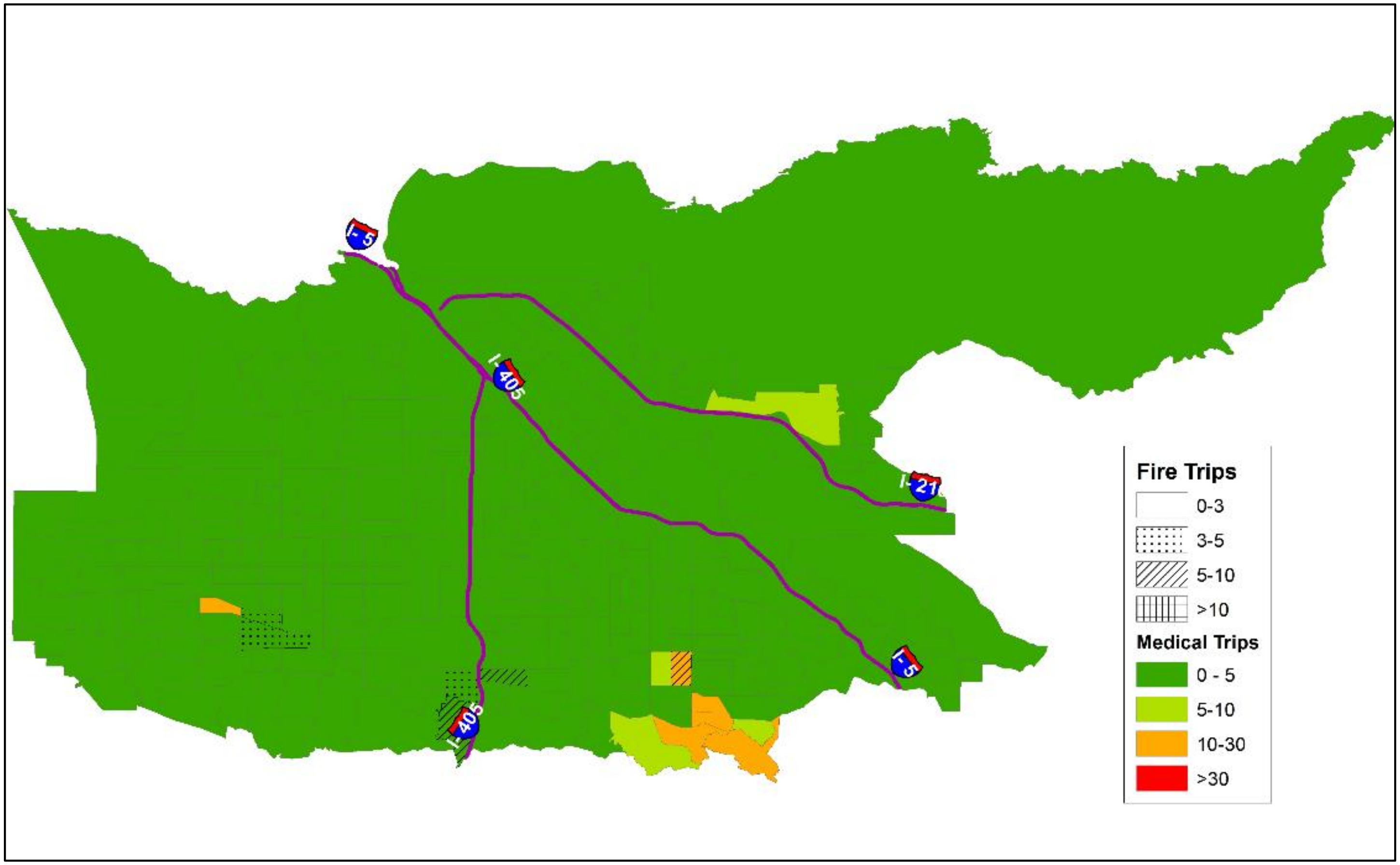


Figure 18 Differences in Travel Time for Medical and Fire Trips for Scenario S4

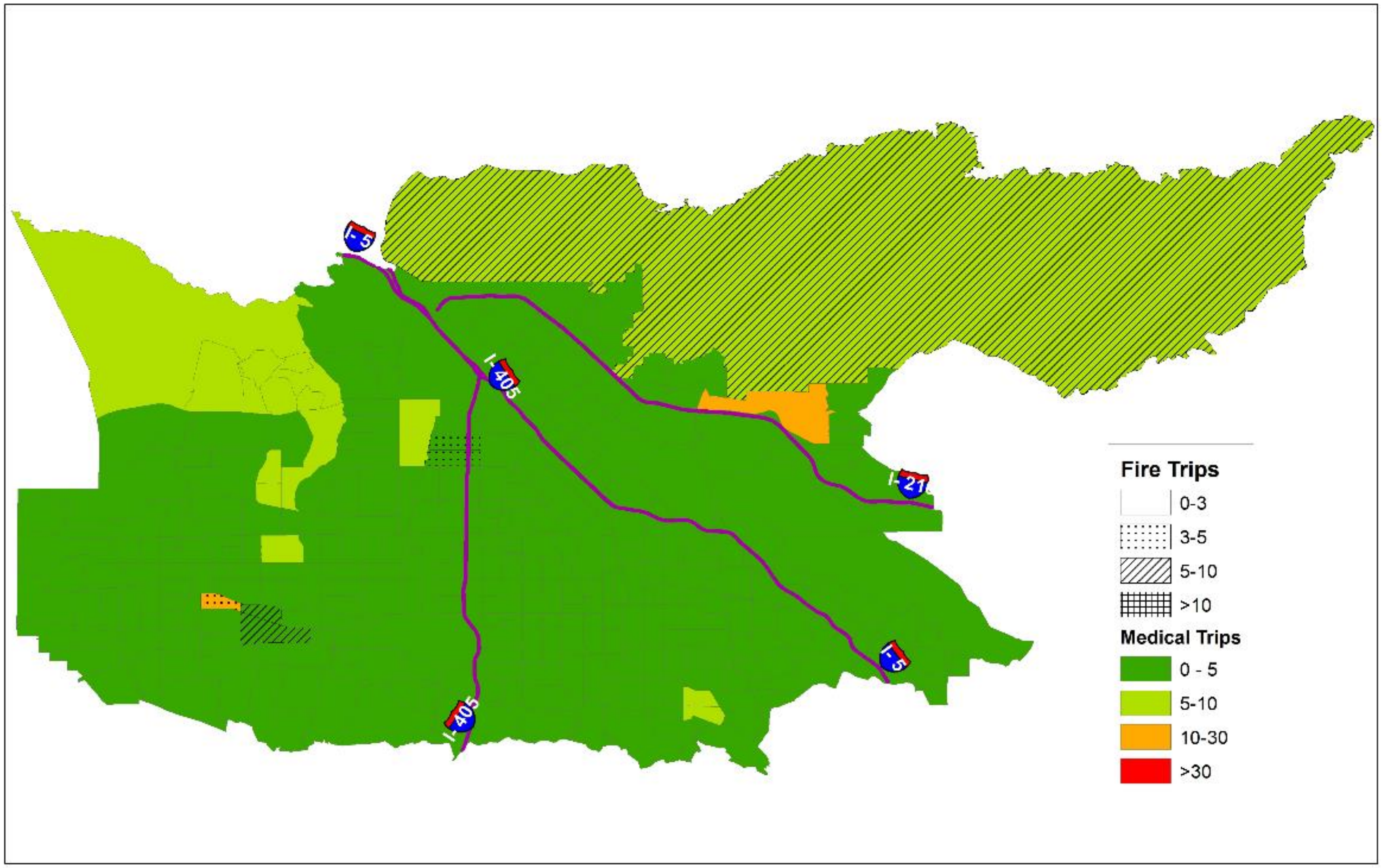
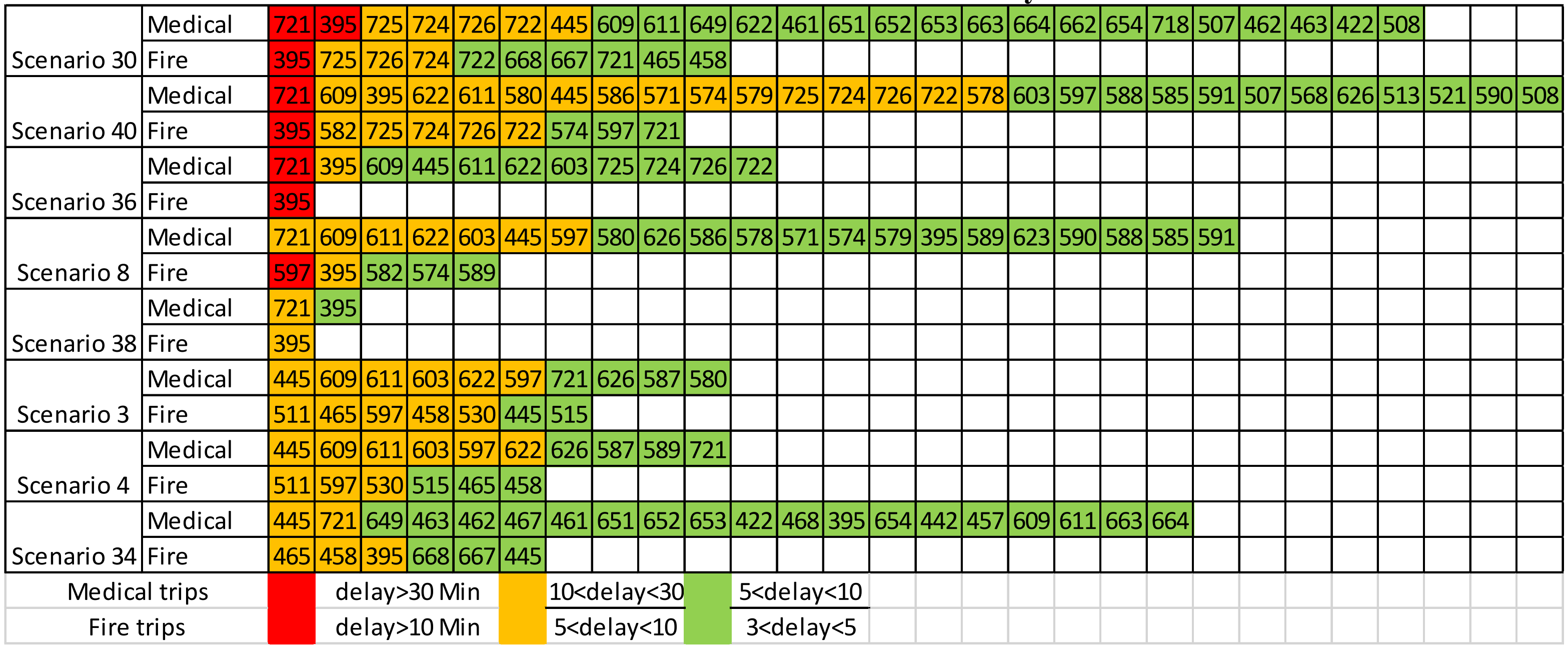


Figure 19 Differences in Travel Time for Medical and Fire Trips for Scenario S34

Table 21 TAZs with the Greatest Delay



Scenario 30	Medical	721	395	725	724	726	722	445	609	611	649	622	461	651	652	653	663	664	662	654	718	507	462	463	422	508			
	Fire	395	725	726	724	722	668	667	721	465	458																		
Scenario 40	Medical	721	609	395	622	611	580	445	586	571	574	579	725	724	726	722	578	603	597	588	585	591	507	568	626	513	521	590	508
	Fire	395	582	725	724	726	722	574	597	721																			
Scenario 36	Medical	721	395	609	445	611	622	603	725	724	726	722																	
	Fire	395																											
Scenario 8	Medical	721	609	611	622	603	445	597	580	626	586	578	571	574	579	395	589	623	590	588	585	591							
	Fire	597	395	582	574	589																							
Scenario 38	Medical	721	395																										
	Fire	395																											
Scenario 3	Medical	445	609	611	603	622	597	721	626	587	580																		
	Fire	511	465	597	458	530	445	515																					
Scenario 4	Medical	445	609	611	603	597	622	626	587	589	721																		
	Fire	511	597	530	515	465	458																						
Scenario 34	Medical	445	721	649	463	462	467	461	651	652	653	422	468	395	654	442	457	609	611	663	664								
	Fire	465	458	395	668	667	445																						
Medical trips		🟥	delay>30 Min				🟧	10<delay<30			🟩	5<delay<10																	
Fire trips		🟥	delay>10 Min				🟧	5<delay<10			🟩	3<delay<5																	

Table 22 Frequency of TAZs Appearance in Greatest Delay Table

TAZ	395	721	445	597	609	611	622	603	722	724	725	726	458	465	574	626
Frequency	12	10	9	8	7	7	6	5	5	5	5	5	4	4	4	4

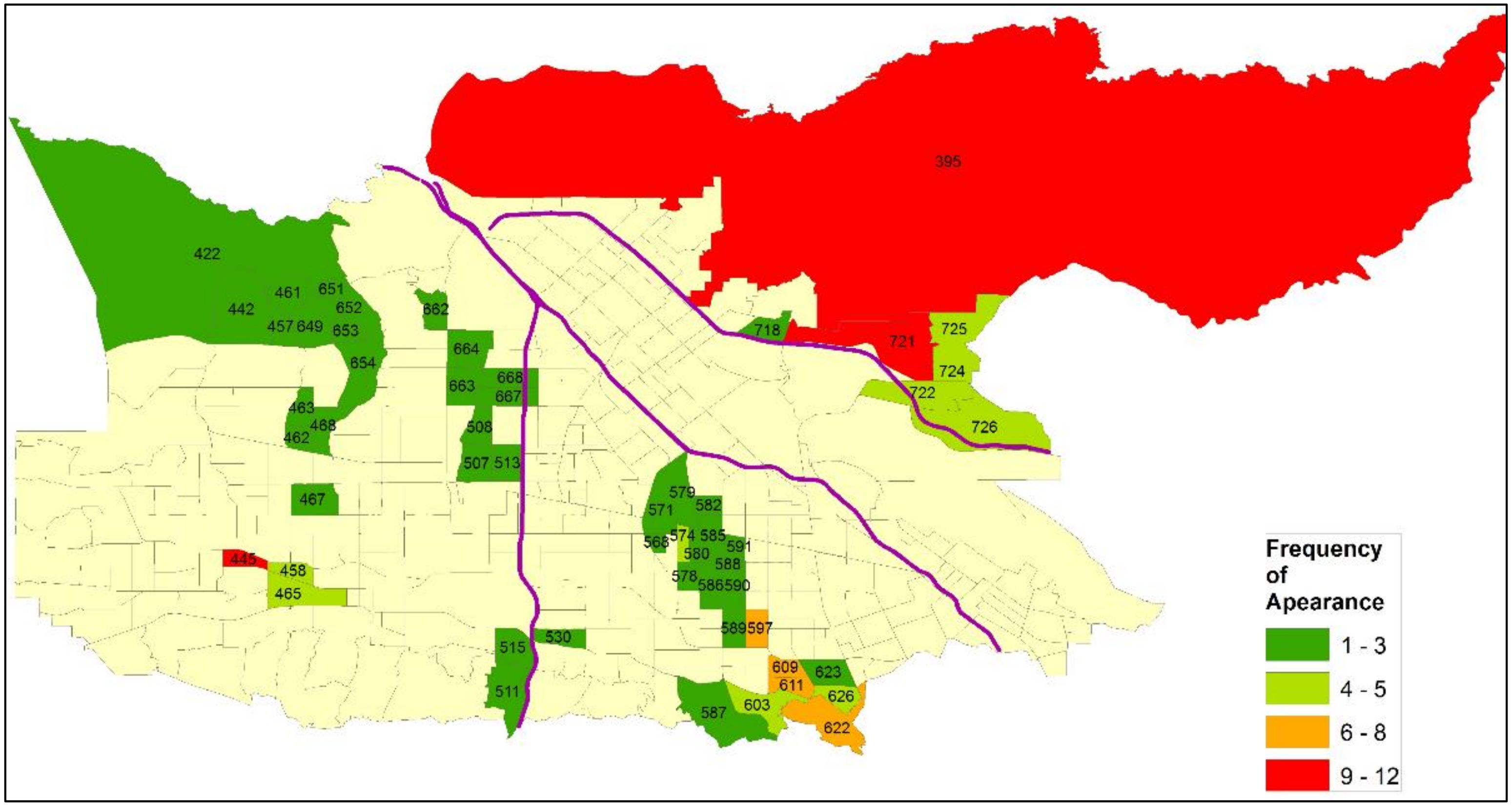


Figure 20 TAZs with Frequent Delays

5.5 Performance Measures

5.5.1 Travel Delay

The travel delay is an aggregate measure of delay across the network for each of the scenarios. The analysis presented in the previous section identified scenarios where maximum delay exceeded 10 minutes for further analysis. Of the eight scenarios identified, six scenarios also produced the largest total travel delay in the network.

5.5.2 Other Performance Measures

The Disruption Index and Revised Disruption Index were also calculated for all 47 scenarios. The Disruption Index is shown in Table 24. The chart in Figure 18 shows the Disruption Index for 47 scenarios plotting in descending order. The maximum Disruption Index (1.07) shows a 7% increase in total travel time in the network system. The figure shows that for the majority of scenarios, the Disruption Index is 1, meaning the network is generally responding well to the disaster in terms of travel time. All scenarios identified as having a maximum increase in travel time exceeding 10 minutes have a Disruption Index greater than 1. As in the discussion of the travel delay, six of the eight scenarios were also identified as the six scenarios with the largest Disruption Index for the network.

Table 23 Travel Delay for All Scenarios (veh- min)

Scenarios	TD(Veh-Min)	Scenarios	TD(Veh-Min)
S1	0	S25	0
S2	3808	S26	0
S3	16192	S27	0
S4	13791	S28	0
S5	2134	S29	5834
S6	46	S30	21928
S7	3	S31	0
S8	14356	S32	0
S9	0	S33	0
S10	243	S34	11045
S11	7194	S35	1748
S12	0	S36	1924
S13	0	S37	0
S14	0	S38	1302
S15	0	S39	10476
S16	0	S40	20334
S17	0	S41	0
S18	0	S42	0
S19	90	S43	0
S20	15	S44	0
S21	258	S45	3
S22	0	S46	0
S23	263	S47	5
S24	0		

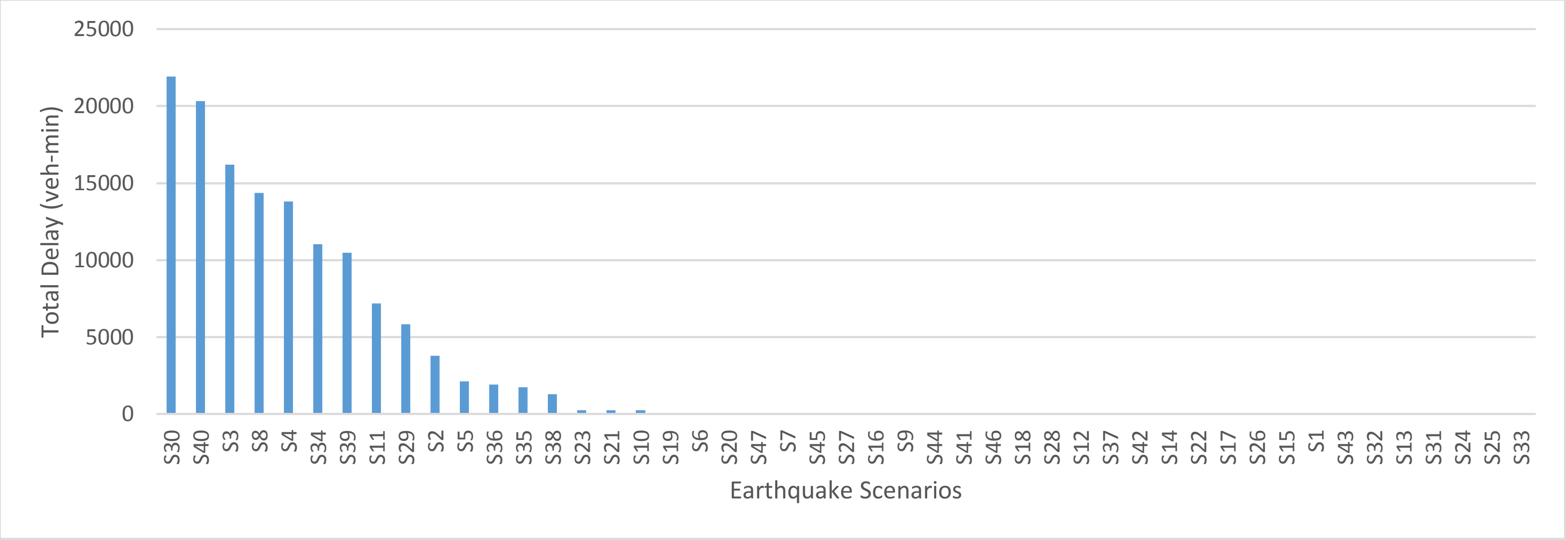


Figure 21 Earthquake Scenarios in Descending Order of Travel Delay

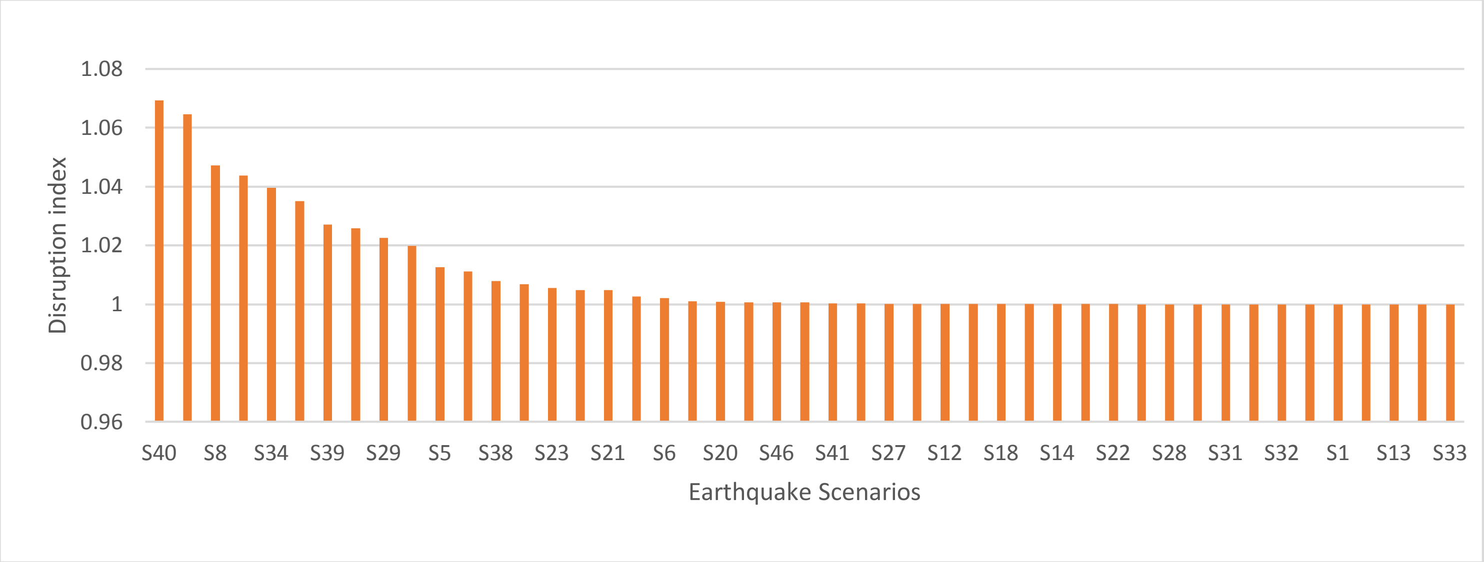


Figure 22 Disruption Index for All Scenarios

Table 24 Disruption Index

Scenarios	DI	Scenarios	DI	Scenarios	DI
S40	1.07	S21	1.00	S14	1.00
S30	1.06	S19	1.00	S26	1.00
S8	1.05	S6	1.00	S22	1.00
S3	1.04	S47	1.00	S17	1.00
S34	1.04	S20	1.00	S28	1.00
S4	1.04	S45	1.00	S37	1.00
S39	1.03	S46	1.00	S31	1.00
S36	1.03	S7	1.00	S15	1.00
S29	1.02	S41	1.00	S32	1.00
S2	1.02	S16	1.00	S43	1.00
S5	1.01	S27	1.00	S1	1.00
S11	1.01	S44	1.00	S25	1.00
S38	1.01	S12	1.00	S13	1.00
S35	1.01	S9	1.00	S24	1.00
S23	1.01	S18	1.00	S33	1.00
S10	1.00	S42	1.00		

The Revised Disruption Index is shown in Figure 19 and Table 25. The Revised Disruption Index shows the increase in vehicle travel time for before and after an earthquake. Six of the eight scenarios with maximum travel time exceeding 10 minutes were also identified as the six of the eight scenarios with the largest revised damage index for the network.

Fifteen scenarios had a DI greater than one and 20 scenarios have an RDI greater than one. The fifteen scenarios are a subset of the 20 scenarios with an RDI greater than one, indicating some consistency in the analysis.

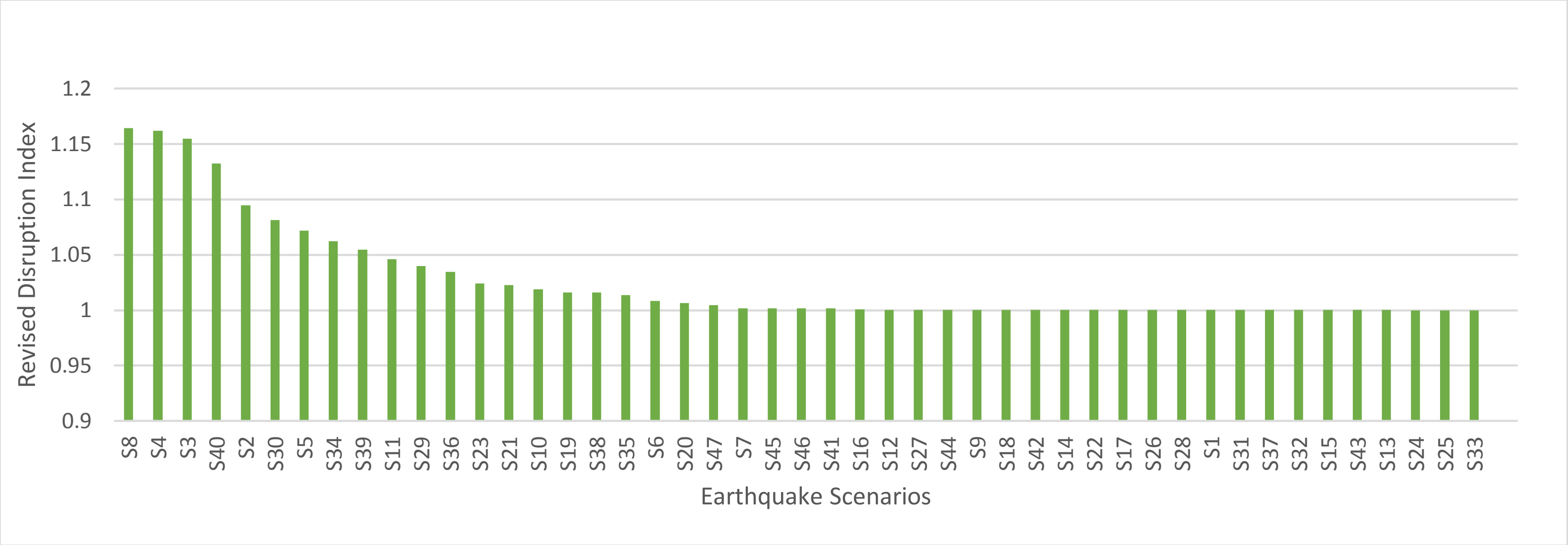


Figure 23 Revised Disruption Index

Table 25 Revised Disruption Index

Scenarios	RDI	Scenarios	RDI	Scenarios	RDI
S8	1.16	S38	1.02	S14	1.00
S4	1.16	S35	1.01	S22	1.00
S3	1.15	S6	1.01	S17	1.00
S40	1.13	S20	1.01	S26	1.00
S2	1.09	S47	1.00	S28	1.00
S30	1.08	S7	1.00	S1	1.00
S5	1.07	S45	1.00	S31	1.00
S34	1.06	S46	1.00	S37	1.00
S39	1.05	S41	1.00	S32	1.00
S11	1.05	S16	1.00	S15	1.00
S29	1.04	S12	1.00	S43	1.00
S36	1.03	S27	1.00	S13	1.00
S23	1.02	S44	1.00	S24	1.00
S21	1.02	S9	1.00	S25	1.00
S10	1.02	S18	1.00	S33	1.00
S19	1.02	S42	1.00		

5.6 Conclusions

In this chapter, the San Fernando Valley area was studied using the methods developed to evaluate the performance of the network after a disaster. At the same time, identifying the most critical links besides providing recommendations for decreasing the travel delay for emergency response trips in the study area.

While the method relies on many assumptions including models embedded within Hazus-MH and relationships between trip making and earthquake damage, the case study explores how the methodology can be used to understand the impact of the earthquake scenarios.

Generally the travel delay, the Disruption Index (1-1.07) and the revised damage index (1-1.16) showed that the network was well-prepared for the disaster.

However, some specific scenarios cause great delay for specific zones. The results of this analysis were shown to reveal the source of delay and provide an opportunity to suggest improvements such as additional emergency services, retrofitting bridges and providing alternative routes. In other words, in this case study, the causes of greatest delay were investigated and appropriate countermeasures in the form of building alternative roads, retrofitting the bridges, and establishing new medical centers were provided.

Based on this type of exploratory analysis, a detailed analysis of the value of potential improvements and changes based on the costs and benefits and the likelihood of the various scenarios.

Chapter 6

DISCUSSION

The methodology presented in Chapter 3 and the case studies (Newark, Delaware, and San Fernando Valley, California) presented in Chapter 4 and 5 are based on many assumptions. They also provide some insights into the factors that influence the behavior of emergency organizations responding to an event, the response of the transportation network to the damage from an event, and the added trips by emergency responders. The following sections review the data needed for the analysis, the challenges involved in modeling the trips of emergency responders, the insights provided by the results, and some observations regarding elements missing from the analysis.

6.1 Data

This research was focused on estimating the number of emergency response trips following an earthquake. The method used Hazus-MH outputs and some logical assumptions to forecast the number of emergency response trips after a specific event. The number of emergency response trips was much smaller than the background trips. These background trips were approximated by the number of peak hour trips. For the San Fernando Valley case study, the total trips for emergency responses are between 0 and 2.7% of the background trips.

The distribution of these trips over the hours following the earthquake and the impact of time of day of the event are also important assumptions. For the Newark case study, a proportion of the estimated trips is used based on data from the Kobe earthquake. These trips are assigned to the network to reflect the limited resources, For estimating the number of emergency response trips the current available resources are not considered as a constraint for the San Fernando Valley case study. Therefore, these estimated trips should be considered as the total demand during the response period. In the case that enough resources are available this estimated number can be expected in the first hour after an earthquake. Moreover it is noted that the emergency response demand for different times of day are not the same. In this study the number of emergency response trips are estimated for the afternoon period. This period is considered both for consistency with background traffic and reflecting the worst case scenario. However, a sensitivity analysis for other times of day can be done in future work.

The back ground trips are approximated by PM peak hour traffic. This is based on a study in New Zealand (Walton and Lamb 2009). This study was the only available study that conducted a real survey after the earthquake and estimated the number of individuals' trips after an earthquake. This may also not be accurate for other cases, however it is also intended to reflect a worst case scenario.

6.2 Challenges in Modeling Trips

Unpredictability is a basic feature of natural disasters, specifically earthquakes. A variety of possible events should be considered in a long-term plan. In this research, a limited number of scenarios were considered as the representative of all possible scenarios. However, some details, such as time of day, number of emergency responders available, and the effect of debris on road closure, are not considered in the simulation.

6.3 Insights and Results

The results of this study reveal a few important causes of delay for emergency response trips immediately after an earthquake. Specifically:

1. Relative Magnitude of Emergency Response Trips: Compared with typical peak hour trips generation rates, the number of emergency response trips generated immediately after an earthquake is relatively small. However, damage to the network means that some of these trips are significantly delayed.

2. Relative Magnitude of Different Trip Purposes: Transporting the injured to medical care, firefighting and search and rescue operations are the most significant trip purposes immediately after an earthquake. Utility restoration is relatively insignificant.

3. Network topology: It is shown that in the southern part of the San Fernando Valley, which is surrounded by mountains and is harder to access, huge delays are observed in several scenarios.

4. Allocation of medical centers: Lack of medical centers in some areas causes some large delays, as discussed in the San Fernando Valley case study.

5. Critical bridges: Some bridges serve a number of zones and there is no good alternative if their capacity is reduced or if they simply fail. This is another cause of huge delays. In the San Fernando Valley case study, some of these bridges are identified and retrofitting is recommended.

Finally, the performance of the system is evaluated by two performance measures: Travel Delay and Disruption/Revised Disruption Index. Travel delay was helpful in estimating the cost caused by an earthquake, specifically when the value of time is extremely high. While disruption index gives a general idea of how good the system is responding to a disaster.

For estimating the cost of the damage on the transportation network caused by an earthquake, the cost of delay for emergency response trips should be included. Number of emergency response trips will be used in estimating this cost considering the delay for these trips and value of time for this type of trips. Using the probabilistic method the annual expected value of number of emergency response trips after an earthquake and the delay for these trips can be estimated.

The value of time for emergency response trips is very high and every minute of delay can increase the loss of both property and life. In a report published in the Boston Globe and ,it is claimed that based on the data from building fires reported from 1986 through 2002 across the US, for every one minutes the response time increases the probability of death increases by half a percent. This report is verified by Elaine Allen, a statistics professor at Babson College (Dedman, 2005).This report also claimed that the property damage is tied to response time. As response times increase, the average property damage in a house fire increases quickly. When firefighters arrive within three minutes or less, the average loss is $27,000; at five minutes, the average loss is $34,000; at seven minutes, the average loss is $41,000; and at nine minutes or longer, the average loss is $61,000. No other studies support this data for United States, but similar information exists for the United Kingdom. The chart in Figure 20 was made based on the data extracted from over 13,000 Fire Damage Report

Forms (FDR1s) in 1995 by government consultants Entec UK Ltd. (Dorset Fire Authority, 2008). From the data above, we can deduce that there is a one in six chance (a 0.16 probability) of a death in a dwelling fire where a person is reported as a casualty or a rescue when attended in over 20 minutes, and a 1 in 26 (a 0.038 probability) chance of death per fire when attended in less than 5 minutes. Similar data exists for medical trips.

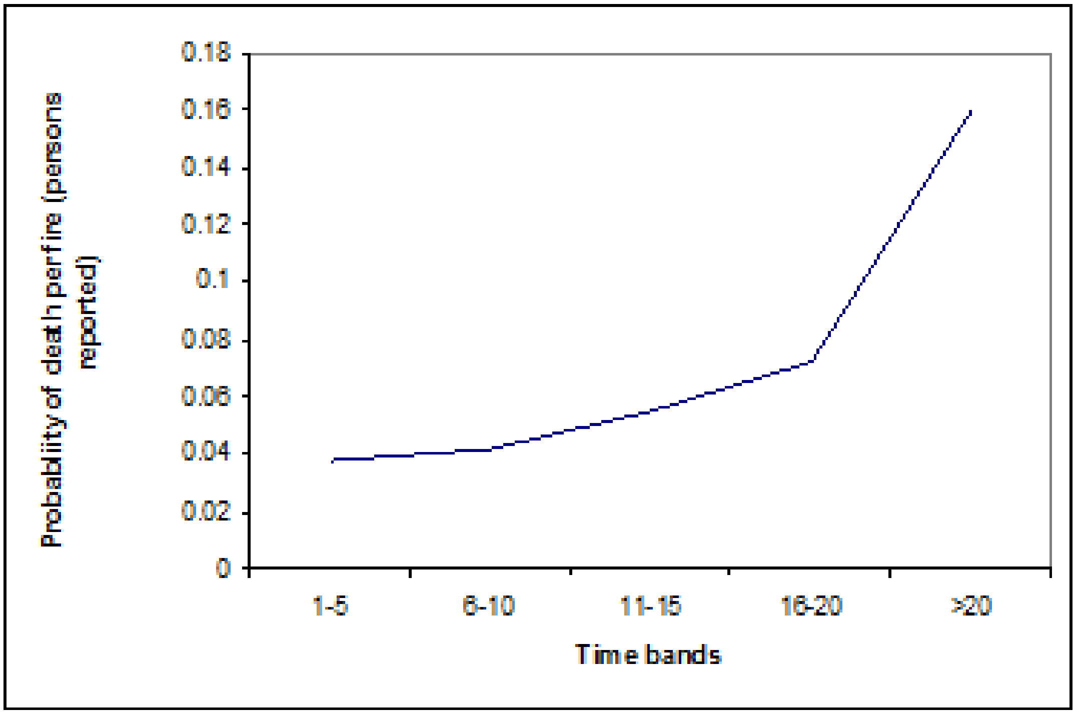


Figure 24 Response Time (minutes from time of alert) Versus Fatality Rate for Dwelling Fires

Similarly, delays for medical trips have the same effect. Studies in this area collectively show that in the case of cardiac arrest, even small increments in call-to-shock time (for example, as little as one minute) can prove detrimental. Conversely, decreases in the amount of call-to-shock time can increase the rate of survival (White, Asplin, Bugliosi, & Hankins, 1996). However, there are a few studies showing the survival rate for other types of medical emergency versus EMS response time.

6.4 Observations

The most important thing missing in this research is an accurate estimate of individuals' trips. For the purpose of this research, the number of individuals' trips is approximated by peak hour traffic data, but this assumption should be more thoroughly explored based on time of the day. It can be argued that this assumption is a worst-case scenario, but understanding how the distribution of trips throughout the day varies can influence decisions to retrofit bridges or develop more medical centers.

6.5 Summary

In the process of this research, we first examined existing post-earthquake transportation supply models, and then developed travel demand models for the time immediately after an earthquake. Then, we integrated existing transportation supply models with these new demand models to assess network performance, and developed case studies demonstrating the role of these models in mitigation and preparedness.

Chapter 7

CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORK

Transportation networks are vital infrastructures, the performance of which has an important effect on the restoration of other systems, and in completing the first wave of emergency response operations, such as medical trips and firefighting.

The damage state of different components of the transportation system, like tunnels, bridges, and pavements for the earthquake hazard, have been studied before. On the demand side, very few studies have focused on the number of trips, their origin and destination, and the objective of the trips immediately after the earthquake.

This research aimed to bring to light the transportation network condition immediately after a disaster. The trips after a disaster can be divided into two general groups:

- Emergency response trips are those are performed by authorities to respond to the disaster and manage the property and human losses.
- Individuals' trips are those are taken by regular people.

This research is focused on emergency response trips and an approximation of the trips by individuals' trips is used.

7.1 Conclusions

For relatively minor events, emergency response trips across the network are not significantly impacted as measured by travel delay and the Disruption Index. However, specific trips may be impacted depending on network topology, the vulnerability of specific facilities, and the location of services such as fire stations and hospitals.

For major events with the potential to cause widespread damage, the network impacts are significant and many emergency response and individuals' trips experience significant delay. Modeling the network provides insights related to the areas experiencing the greatest delays. After identifying these areas, the reasons for delay are explored, and include critical but vulnerable bridges, a lack of alternative routes, and poor access to medical facilities and fire stations, based on distance under normal conditions.

Finally, network resilience in terms of serving emergency response trips, is measured by the Disruption Index and Revised Disruption Index. These indices show relatively small numbers for both case studies, but it can be concluded that for these two networks, the level of service will be acceptable after most possible earthquake scenarios.

7.2 Contributions

The method to estimate the number of emergency response trips is explored and a methodology to estimate the number of emergency response demand trips under specific conditions developed then applied to two case studies.

These demand models can also be used to prepare more efficient plans for the response period, since they provide knowledge about the transportation network conditions during and after a disaster. Simulating a post-earthquake network and adding emergency response demand to that network is the next logical step. The demand models and the integration of the supply and demand has not been explored in the past. The research demonstrated that although emergency response trips are relatively few, they can experience significant delay in a damaged network.

The performance measures, such as the delay occurs in emergency response trips, can be interpreted as economic or human loss. The mitigation plans can be designed to minimize these losses knowing the travel pattern and the problematic areas after the earthquake.

7.3 Future Research

This research can be extended in the future in several ways:

1- Developing a travel demand model for individuals' trips: this research is focused on emergency response trips, however the background traffic by individuals is equally important to estimating an accurate travel time. These trips are likely to vary by time of day and nature of the event, however.

2- Alternative performance measures: Delays covered in this research can be converted to a dollar amount or loss of human lives to be more effective in communicating with policy/decision makers.

3- This research has modeled the transportation network at a macro level. Modeling the network at a meso level by considering all the delays at intersections can help to provide more accurate results.

4- Considering the last point, electricity outages can be considered and simulated.

5- The delay reported in this research is for private cars; specific estimation for emergency response vehicles can be applied.

6- Validation of the models is needed. Ideally, comparing the models to actual field experiences would be best. The survey included in Appendix B serves as a starting point for research along these lines following a specific event.

7- Generalization of the models for use with other hazards such as flooding, tornadoes and hurricanes. These hazards also disrupt the transportation network, which in turn is needed to provide access for emergency responders.

8- A sensitivity analysis for time of day of earthquake occurrence, capacity assigned to each damage state for bridges, the trip rates assigned to each injury or damaged building or fire ignition, and time breaks to find the most delay causing scenarios can help to expand the understanding of the network condition

9- The case of the limited resources can be explored for more accurate results.

10- The utility of the results can be explored in a probabilistic analysis that integrates the scenarios and the impacts to better understand the effectiveness of possible improvements.

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Appendix A

ACRONYMS

BDI – Bridge Damage Index

DI – Disruption Index

EMS – Emergency Medical Services

FSM – Four step model

LA – Los Angeles

LAFD – Los Angeles Fire Department

LDI – Link Damage Index

MCE – Maximum Credible Earthquake

NBI – National Bridge Inventory

PGA – Peak ground acceleration

PSHA – Probabilistic seismic hazard analysis

O-D – Origin destination

RDI – Revised Disruption Index

REDARS – Risks from Earthquake Damage to Roadway Systems

SAR – Search and rescue

SCAG – Southern California Association of Governments

TAZ – Traffic analysis zone

TD – Travel delay

TFA – Total floor area

US&R – Urban search and rescue

Appendix B

GLOSSARY

Damaged: State of the transportation network condition after a disaster; usually means reduction in the capacity of some of the components of the network.

Fragility Curve: The fragility curves are used to represent the probabilities that the structural damages, under various levels of seismic excitation, exceed specified damage states.

Link Capacity: A maximum flow that a link can carry. In the case of roads, it is often taken to be the rate at which a queue of cars discharges over a stop line.

Performance Measures: Indicators for assessing needs, evaluating system performance, and simply communicating with customers and other stakeholders.

Undamaged (Normal): The transportation network condition before a disaster.

Appendix C

PRELIMINARY SURVEY QUESTIONNAIRE

Protocol Title: A Survey to Understand the Process of Emergency Response Operations

Principal Investigator

Name: Sekine Rahimian

Department/Center: Dept of Civil and Environmental Engineering

Contact Phone Number: 302-831-0561

Email Address: sekine@udel.edu

Advisor (if student PI):

Name: Sue McNeil

Contact Phone Number: 302 831 6578

Email Address: smcneil@udel.edu

Other Investigators: None

Investigator Assurance:

By submitting this protocol, I acknowledge that this project will be conducted in strict accordance with the procedures described. I will not make any modifications to this protocol without prior approval by the HSRB. Should any unanticipated problems involving risk to subjects, including breaches of guaranteed confidentiality occur during this project, I will report such events to the Chair, Human Subjects Review Board immediately.

1. **Is this project externally funded?**

If so, please list the funding source: No

2. **Project Staff**

Please list personnel, including students, who will be working with human subjects on this protocol (insert additional rows as needed):

NAME	**ROLE**	**HS TRAINING COMPLETE?**
Sekine Rahimian	Graduate Research Assistant	Yes
Sue McNeil	Advisor	Yes

3. **Special Populations**

Does this project involve any of the following?

Research on Children? No

Research with Prisoners? No

Research with any other vulnerable population (please describe)? No

4. **RESEARCH ABSTRACT** Please provide a brief description in LAY language (understandable to an 8th grade student) of the aims of this project.

This research is designed to understand the process of emergency response operations after a disaster, in this particular case, an earthquake. This information estimates the number of trips that should be made by emergency responders after a disaster. The final aim of the project is finding the total demand for the transportation system (emergency response trips) in the special case of post-earthquake situation and evaluating the transportation system performance for that case.

5. **PROCEDURES** Describe all procedures involving human subjects for this protocol. Include copies of all surveys and research measures.

The survey will be conducted via e-mail and telephone.

Draft interview protocol is attached.

6. **STUDY POPULATION AND RECRUITMENT**

Describe who and how many subjects will be invited to participate. Include age, gender and other pertinent information. Attach all recruitment fliers, letters, or other recruitment materials to be used.

County Emergency Center’s Personnel: 2 responders

County Emergency Center’s Personnel: 2 responders

Fire Station's Chiefs: 2 responders

Describe what exclusionary criteria, if any will be applied.

None.

Describe what (if any) conditions will result in PI termination of subject participation.

Subject chooses to terminate participation.

7. RISKS AND BENEFITS

Describe the risks to participants (risks listed here should be included in the consent document). If risk is more than minimal, please justify.

Risks are minimal as a survey is used to identify and characterize activities involved in the emergency response to a disaster. The subjects are not being brought to any specific location, nor are they being asked to do anything other than offer their opinions about the activities that undertaken. No personal information is recorded.

What steps will be taken to minimize risks?

The risks posed to the respondents are minimal since the survey is used simply to gather opinions related to infrastructure performance. All efforts will be made to ensure that the information collected will remain confidential.

Describe any direct benefits to participants.

None

Describe any future benefits to this class of participants.

The intent is that we will eventually understand how to be better prepared to respond to disasters.

If there is a Data Monitoring Committee (DMC) in place for this project, please describe when and how often it meets.

No.

8. COMPENSATION

Will participants be compensated for participation?

No

If so, please include details.

9. DATA

Will subjects be anonymous to the researcher?

No

If subjects are identifiable, will their identities be kept confidential?

Yes, and the data will be used only in an aggregate form.

How and how long will data be stored?

The data will be stored for the duration of the project.

How will data be destroyed?

Electronic copies will be deleted. If any paper copies are made, they will be shredded.

How will data be analyzed and reported?

The data will be analyzed and reported in an aggregate form to identify variables to include in a model.

10. CONFIDENTIALITY

Will participants be audiotaped, photographed or videotaped during this study?

No

How will subject identity be protected?

Individual identifiers will not be retained. The data will be aggregated and, therefore, the subject's identity will be protected.

Is there a Certificate of Confidentiality in place for this project? (If so, please provide a copy).

Not applicable

11. CONSENT and ASSENT

____ Consent forms will be used and are attached for review.

____ Additionally, child assent forms will be used and are attached.

__X__ Consent forms will not be used (Justify request for waiver).

This protocol is a request for an exemption.

12. **Other IRB Approval**

Has this protocol been submitted to any other IRBs?

No

If so, please list along with protocol title, number, and expiration date.

13. **Supporting Documentation**

Please list all additional documents uploaded to IRBNet in support of this application.

Need to include your interview protocol.

Questionnaire:

We are conducting research on trips made by emergency responders immediately following a disaster to better understand the impacts of damage to the transportation network and opportunities to make the transportation more accessible to speed up emergency response. Based on your experience as an emergency responder, we would like you to answer a series of questions. The questions range from questions about how emergency response is organized to your opinions about specific activities. Please answer the questions in the questionnaire to your convenient extent. Your valuable detailed explanation for each question will be asked via telephone later.

Participation in the survey is completely voluntary and may be terminated at any time. Your response is confidential and will used to provide summary data and help guide the development of models.

The survey/interview will take about xx minutes to complete. If you have any questions you may contact Sekine Rahimian at sekine@udel.edu.

Which one of these statements is closer to what actually happens? (Please correct them). That is please confirm the accuracy of the statements below or correct them, or responds to the questions:

1. Emergency operations start immediately after the earthquake and the firefighters start to respond to the incident as follows:

a) As they can see the need or
b) In response to information from a group doing rapid damage assessment. Information will take about ____minutes to reach the fire fighters, or
c) After checking in with the EOC. This usually takes ____ minutes.

2. The following is a list of emergency operations done by fire centers after an earthquake. Please complete the list:

   1) Structural and other fires
   2) Building collapse and rescue
   3) Vehicular accident
   4) Emergency medical services

3. **For structural fires**:

This is the first priority of the firefighters, especially when structural fires have the potential of spreading. Initially, this operation starts immediately after an earthquake and one fire truck will be sent to each incident. More resources will be sent as requested by the first responders.

4. Are your center's resources sufficient to respond to a moderate earthquake?
5. How do you choose the route to the incident site?

6. Do you send out all your resources to respond to reported incidents or you keep some of resources in reserve to strategically respond to other incidents?

7. How many fire engine/trucks do you have?

8. If a moderate earthquake occurred, how many personnel do you think would be available to assist with emergency response? (How many on-duty personnel do you have, how many will be in the center in ____ minutes?)

9. How big is your area of responsibility in terms of

Area

Population

Number of census tracts??

10. **Building collapse and rescue**:

This operation is done after rapid damage assessment or EOC information is sent. The number of personnel and vehicles sent to an incident site depends on the number of people in the building and the number of stories; one vehicle will be sent to each site initially and these extra resources will be sent on request.

11. What vehicles do you use to respond to a collapsed building?

12. On average, how many personnel and resources would you send for search and rescue for each collapsed building? What are the important factors in identifying the number of vehicles you are sending?

The number of stories

The number of potential victims

13. What other vehicles and personnel should be sent to support this operation?

14. **Emergency Medical Services**:

Emergency medical services are for serving injured people before sending them to medical centers and transferring them to the medical centers. Please explain the process of serving injured people:

a) Is the first request for medical services sent to the fire centers by other groups, like search and rescue and firefighters?
b) How many vehicles and personnel do you send initially?
c) Do you have any estimates of the percentage of injured people that would be transferred by ambulances?
d) How many personnel/vehicles do you send for each injured person?

15. Are there other trips made by emergency responders that should be considered?