12-2013

Optimal Retrofit Strategy Design for Highway Bridges Under Seismic Hazards: A Case Study of Charleston, SC

Shawn Parmelee
Clemson University, sparmel@clemson.edu

Recommended Citation
Parmelee, Shawn, "Optimal Retrofit Strategy Design for Highway Bridges Under Seismic Hazards: A Case Study of Charleston, SC" (2013). *All Theses*. 1771.
https://tigerprints.clemson.edu/all_theses/1771

OPTIMAL RETROFIT STRATEGY DESIGN FOR HIGHWAY BRIDGES UNDER SEISMIC HAZARDS: A CASE STUDY OF CHARLESTON, SC

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

---

by
Shawn Michael Parmelee
December 2013

Accepted by:
Dr. Yongxi (Eric) Huang, Co-Committee Chair
Dr. Weichiang Pang, Co-Committee Chair
Dr. Mashrur Chowdhury

ABSTRACT

A significant number of US highway bridges are inadequate for seismic loads and could be seriously damaged or collapse during a relatively small earthquake. On the most recent infrastructure report card from the American Society of Civil Engineers (ASCE), one-third of the bridges in the United States are deemed to be structurally deficient. To improve this situation, at-risk bridges must be identified, evaluated, and effective retrofitting programs implemented to reduce their seismic vulnerabilities. In practice, the Federal Highway Administration uses the expected damage method and indices method to assess the condition of bridges. These methods compare the severity of expected damage for each at-risk bridge and the bridges with the highest expected damage will receive the highest priority for retrofitting. However, these methods ignore the crucial effects of traffic networks on the highway bridge's importance. Bridge failures or even capacity reductions may redistribute the traffic of the entire network. This research develops a new retrofit strategy decision scheme for highway bridges under seismic hazards and seamlessly integrates the scenario-based seismic analysis of bridges and the traffic network into the proposed optimization modeling framework. A full spectrum of bridge retrofit strategies are considered based on explicit structural assessment for each seismic damage state. A simplified four-bridge network is used to validate the model, and then a modified version of the validated model is applied to the bridge network in Charleston, SC to illustrate the applicability of the model. The results of the case study justify the importance of taking a system viewpoint in the retrofit

strategy decision process and the benefit of using the developed model in the retrofit decision making process

DEDICATION

This work is dedicated to my parents, Daniel and Stacey Parmelee, for supporting me and always making me strive to do my best. Without them I would not be the person, or be the where I am today. It is also dedicated to my wife, Emily, for her patience and always supporting me throughout the entirety of my research.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation, under Grant No. NSF-1011478. The views and conclusions contained in this document are those of the writers and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the National Science Foundation.

TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

Many U.S. highway bridges, in particular older bridges that predate major changes to seismic code provisions, are inadequate for seismic loads and could be seriously damaged or suffer collapse during a relatively moderate intensity earthquake (*1*). On the most recent infrastructure report card from the American Society of Civil Engineers (ASCE), one-third of the bridges the United States are deemed structurally deficient (*2*). In the past, major structural damage has occurred to highway bridges due to earthquakes causing for millions of dollars economic loss in various states, such as Alaska, California, Washington, and Oregon (*1*). To improve this situation, at-risk bridges must be identified, evaluated, and retrofitting programs must be implemented to reduce the seismic vulnerability of critical bridges (*1*).

The main bridge components to be considered under the retrofit strategies are the bridge's superstructure, substructure, and foundation. There are various retrofitting methods in use today and many upcoming methods still being tested to determine their effectiveness. The main goals of bridge seismic retrofits are focused on the following (*1*):

- strengthening bridge components
- improvement of displacement capacity
- limiting forces on major bridge components
- modification of the bridge response

- site remediation by ground movement
- acceptance or control of damage to specific components

Retrofitting all at-risk bridges is neither practical nor economical. Thus, it is important for the transportation stakeholders (e.g., the federal/state departments of transportation or DOT) to determine the best action to take in order to maximize the return (e.g., post-disaster traffic conditions) of the retrofit expenditures (*3*, *4*). The retrofit decision making process is challenging, which is essentially a resource allocation problem under uncertainty (*5*). The first challenge is that the resources including budget, human resources, and material supplies are all limited. The second challenge is the uncertainty caused by the retrofit decision being about the future. The future cannot be predicted with any true certainty, so this uncertainty is transferred to the retrofit decision process.

In practice, the Federal Highway Administration uses the expected damage method and the indices method to determine which bridges are to receive retrofitting procedures. The expected damage method compares the severity of expected damage for each at-risk bridge and the bridges with the highest expected damage will receive the highest priority for retrofitting (*1*, *6*). While the indices method uses indices to characterize the structure vulnerability and hazard level of the bridge (*1*). These indices are then combined to generate a rating from 0 to 10 for each bridge, and are used to determine the priority for retrofitting. These methods provide quantitative results on the expected damage and direct economic losses; however, they ignore the crucial effects of traffic networks on the importance of highway bridges. Bridge failures or even capacity reductions may redistribute the traffic over the entire network. Thus, a bridge retrofit strategy based solely on the severity of expected damage may not lead to optimal solution from a system perspective (*7*) and an integrated retrofit decision scheme taken on the system level should be considered.

In this research, the goal was to develop a new yet practical retrofit program for highway bridges under seismic hazards, which explicitly integrates the expected damage severity and the adverse impact on the traffic network into the decision making scheme. The analysis considers a full spectrum of bridge retrofit strategies that are based on explicit bridge structural assessments for each possible seismic damage state. The optimization model will indicate what retrofit strategy applies to which bridge. The goal is to minimize the total cost incurred by retrofitting the bridges and the subsequent expected damage cost, while satisfying a predefined traffic throughput. It is important to note that both retrofit and expected damage costs are included in the objective for achieving the overall cost-effective retrofit strategies, since a retrofit strategy that is low-cost in retrofitting may have high- cost damages in the aftermath of an earthquake. A simplified four-bridge network was used to validate the model, and a modified version of the model was applied to Charleston, SC to demonstrate the applicability of the model. Although the model is demonstrated in Charleston, SC, it has been developed in general terms for the purpose of being able to be applied to any region or transportation network setup. The results of this thesis will justify the system viewpoint in retrofit strategy decision process.

The following chapters describe the evolution and performance of the developed model. Chapter 2 discusses what is currently published regarding the bridge seismic damage states, retrofit strategies, resource allocation, maximum concurrent flow problem, and the current state of Charleston's infrastructure. The optimization model is presented and discussed in Chapter 3, and demonstrated on the simple four-bridge network. Also, Chapter 3 describes the data inputs for the network, followed by numerical results with analysis. Chapter 4 describes the application of the model to the Charleston area, followed by the numerical results with analysis. Chapter 5 summarizes the research findings and outlines possible future research efforts.

CHAPTER TWO

LITERATURE REVIEW

2.1 Bridge Structural Systems

2.1.1 *Damage States*

The consequences of damage sustained by a bridge during an earthquake can range from minor to severe. The impacts of a bridge collapse are clearly seen in the risk to safety and the monetary value to replace the bridge, while less severe damage has subtle but costly consequences. A bridge closure, even temporary, can have tremendous consequences as bridges often provide vital links in a transportation network. A closure of a bridge may impair emergency response operations in the aftermath of an earthquake and have an economic impact that continually builds. The economic impact can increase with the length of time the bridge is closed due to, the economic importance of the traffic using the route, the traffic delay caused by following alternate routes, and the replacement cost for the bridge. In this research, five distinct damage states (i.e., none, minor, moderate, extensive and complete) were adopted as defined in the earthquake loss estimation model in HAZUS (Hazards-United States) for highway bridges (*8*). The damages states are described as follows:

- **None** (d0) – No Damage.
- **Minor** (d1) – Minor cracking and spalling to the abutment, cracks in shear keys at abutments minor spalling and cracks at hinges, minor spalling at the column or minor cracking to the deck.

- **Moderate** (d2) – Any column experiencing moderate cracking and spalling, moderate movement of the abutment, extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating rocker bearing failure or moderate settlement of the approach.
- **Extensive** (d3) – Any column degrading without collapse, significant residual movement at connections, or major settlement approach, vertical offset of the abutment, differential settlement at connections, or shear failure at abutments.
- **Complete** (d4) – Any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, or tilting of substructure due to foundation failure.

2.2 Bridge Retrofitting Strategies

Bridge damage classifications and possible retrofit strategies are identified in the Seismic Retrofitting Manual for Highway Bridges (*9*). Four areas of retrofit strategies considered in this research are defined as follows in addition to the "do nothing" alternative. A higher numbered, or enhanced, strategy is more costly but leads to a more resilient structure in the aftermath of an earthquake.

- Strategy 0 (S0): Do Nothing
- Strategy 1 (S1): Superstructure Retrofits
- Strategy 2 (S2): Superstructure and Substructure Retrofits
- Strategy 3 (S3): Superstructure, Substructure, and Foundation Retrofits
- Strategy 4 (S4): Complete Bridge Replacement

2.2.1 *Do Nothing and Full Replacement Options*

When retrofitting a seismically deficient bridge, two possible solutions, at opposite ends of the spectrum, should be kept in mind: the ‘do-nothing’ and ‘full-replacement’ options.

The ‘do-nothing’ option requires the acceptance of damage during a future earthquake. This will be a relatively straightforward decision if the expected damage is not a threat to life safety (*1*). The most likely cause of loss of life is total collapse of a span, but this is a relatively rare event. For example, the toppling or failure of individual bearings will not necessarily lead to collapse if the bearing seats are wide enough to catch the superstructure. Similarly, foundation failures are unlikely to cause collapse, unless the ground deformations are extremely large due to widespread liquefaction or massive ground failure such as fault rupture. Fortunately, these occurrences are rare. Nevertheless, judgment should be used when assessing collapse potential and to the extent possible.

The ‘full-replacement’ option, on the opposite end of the spectrum, may be an attractive option, particularly when the cost of retrofit is on the same order of magnitude as the replacement cost of the bridge. Full replacement is generally considered whenever the retrofit costs approach 60 to 70 percent of a new bridge and may become even more attractive if the structure has non-seismic structural deficiencies and is functionally obsolete (*1*). However, the cost of demolition and any costs associated with control and rerouting of traffic should be considered as part of the cost of the replacement alternative.

2.2.2 *Superstructure Retrofitting*

The most common and serious seismic deficiencies are often found at the bearings and bearing seats, and can potentially lead to a loss of support and collapse of the bridge (*1*). In order to prevent failure of bearing and expansion joints of a bridge, several relatively simple and inexpensive actions can be taken. Retrofitting measures include restraining devices, bearing seat extensions, bearing strengthening, and bearing replacement. The main retrofit seen in this area is the use of restrainers to tie different parts of the bridge together (*9*). The three main types of restrainers are longitudinal joint, transverse bearing, and vertical motion restrainers. Longitudinal joint restrainers are installed to limit the relative displacement at joints and decrease the chance of losing support or unseating at these locations. Transverse bearing restrainers are a necessity in most cases. They are designed to keep the superstructure from sliding off its supports if the bearings were to fail. Finally, vertical motion restrainers are designed to prevent uplift that could cause damage to the bridge (See Figure 2.1).

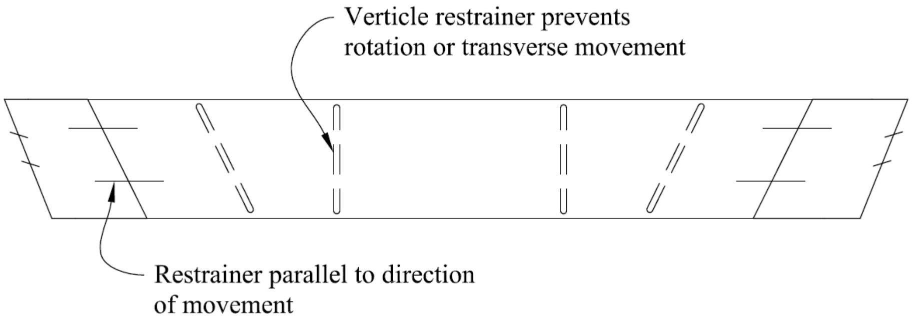


Figure 2.1 Example of Effective Superstructure Retrofitting (*1*)

If it is impractical to restrain the movement of the bridge to prevent losing support at bearings additional retrofitting methods can be done. These include bearing seat extensions and replacing the bearing. Bearings should be replaced if their failure will result in collapse or loss of function of the superstructure. Replacing or strengthening bearings and their accompanying restraining components should be capable of resisting the longitudinal, transverse, and vertical forces acting on the bridge during an earthquake event.

2.2.3 *Substructure Retrofitting*

Bridge substructure (columns and cap beams) retrofitting measures have been the subject of intensive research and development, leading to great insight into the effectiveness of different retrofitting strategies on the substructure of bridges (*1*, *10*). For example, columns are commonly deficient in flexural ductility and shear strength. A significant portion of the initial column research provided insight into the effectiveness of different retrofit measures to improve both shear strength and flexural ductility of reinforced concrete bridge columns (*11*). As a result, standards were developed for evaluating bridge columns and standard techniques were adopted for improving their ductility and shear resistance (*12*). This was accomplished by encasing reinforced concrete columns in circular or elliptical steel shells (steel jacketing) or by wrapping them with fiber composite materials (See Figure 2.2). These methods were shown in the laboratory to improve flexural ductility and shear strength and to prevent the failure of starter bar splices located within potential plastic hinge zones. They have now been implemented on a large number of California bridges, and been proved to be effective in practice by preventing several bridge failures during the 1994 Northridge earthquake (*13*).

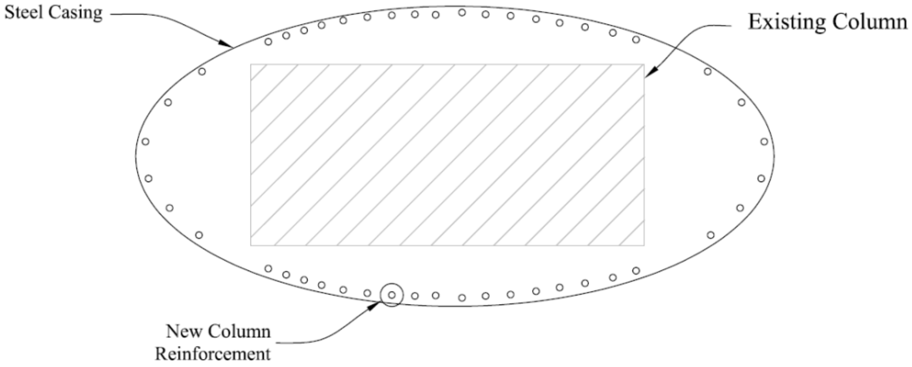


Figure 2.2 Example of Effective Substructure Retrofitting (*1*)

Steel jacketing significantly improves the flexural strength of the column by using passive confinement. Two steel plates are placed around the area to be retrofitted and the gap in between is filled with concrete adding support to the column. Composite fiberglass/epoxy wrapping has been successful in enhancing the flexural ductility and shear strength of columns. Similarly to steel jacketing, the composite fiberglass/epoxy wrapping is wrapped around the critical areas of the column (*9*).

2.2.4 Foundation Retrofitting

Abutments, footings, and foundations connect the bridge to the earth, and are the means by which a bridge feels the effects of an earthquake. Most foundation failures that occur during earthquakes can be attributed to the instability of the supporting soil due to liquefaction, lateral spreading, fault movement, or a landslide (*1*). Very few bridges have collapsed due to structural failure of foundation components, but there are instances where retrofitting is required.

Footings that support columns may be structurally unable to resist the forces transmitted from those columns. This usually occurs when there is a lack of reinforcement in the top of the footing (*1*). Structural strengthening of the footing will be necessary to force plastic hinging into the column. There are also cases when movements of existing footings can result in instability of the pier and the capacity of the pier foundations needs to be increased. Instability caused by liquefaction or lateral spreading can also be addressed by providing a strong foundation (*1*). Retrofitting footings is the most expensive aspect of bridge seismic upgrading. Deficiencies are found in flexural strength, shear strength, footing/column shear strength, anchorage of column rebar, pile capacity, and overturning resistance (See Figure 2.3). Retrofitting strategies include overlaying of reinforced concrete, increasing the depth of the footing, and prestressing by drilling ducts or new concrete on the sides (*9*).

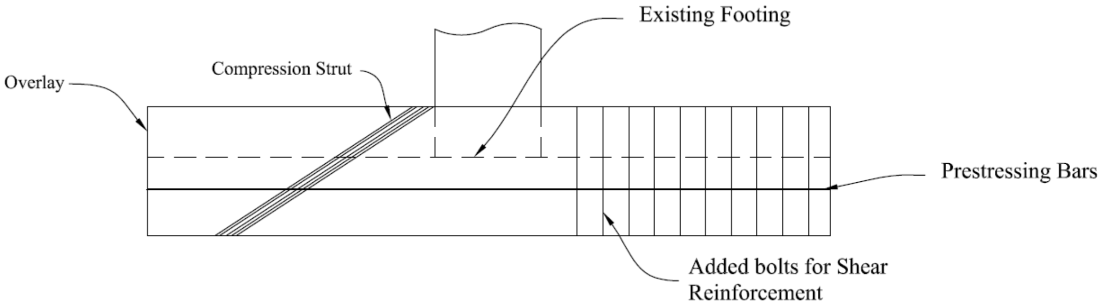


Figure 2.3 Example of Effective Foundation Retrofitting (*1*)

2.3 <u>Transportation System Analysis</u>

2.3.1 *Resource Allocation*

The difficulty associated with the selection of retrofitting strategies is resource allocation. Transportation infrastructure planning can have a significant impact on urban development, but is governed by uncertainty and limited resources. It is neither practical nor economical to retrofit all bridges to enhance their performance hedging against earthquakes. As the gap between the total budgetary resources available for transportation infrastructure projects and the need for new construction and upgrading projects for highway infrastructure widens, it is important for public administrators to maximize the return for the expenditures on transportation investments by selecting the most cost benefit projects (*3)*. The most challenging task for public administrators of the state Departments of Transportation (DOT), who are usually responsible for the management, inspection, and maintenance of transportation infrastructure under a limited budget, is to decide which projects to fund in a prioritized order (*4*). The selection process is difficult because various factors must be considered simultaneously when selecting a subset of projects from a set of feasible candidate projects. When projects are selected based only on cost minimization, the selection process is likely to overlook some salient aspects, such as the perceived project value and chance of success (*5*). This makes the project selection problem a multi-criteria decision making problem, making it difficult to estimate the needed project resources. These resources most commonly include construction costs, human resources, and material supplies. A majority of the time public administrators fund projects without a complete knowledge of all the necessary information. Accordingly, developing and using evaluation criteria and performance metrics can drive effective project selection (*5*). To do this the developed model incorporates a modified version of the expected damage method developed by the Federal Highway Administration (*1*) to allow for the selection of a subset of retrofit strategies to be selected from the set of feasible candidates.

2.3.2 *Maximum Concurrent Flow Problem*

The maximum concurrent flow problem (MCFP) is a multicommodity flow problem in which every pair of entities can send and receive flow concurrently (*14*). The ratio of the flow supplied between a pair of entities to the predefined demand for that pair is called throughput and must be the same for all pairs of entities for a concurrent flow. The MCFP objective is to maximize the throughput, subject to the capacity constraints (*14*). The most common applications include packet-switched networks (*15, 16, 17*), and cluster analysis (*18*).

Consider a network of entities (cities, computers, etc.) in which there exists a demand for flow between all pairs of entities. The flow is sustained through channels with certain capacities. For the MCFP, it is desired to assign flow to each route of the network, such that the ratio of the flow supplied between each pair of entities to the demand between that pair (termed the throughput) is the same for all pairs of entities (*14*). This flow assignment must respect the capacity constraints; that is, the total flow through a channel should not exceed its capacity. The MCFP is to assign flow to the routes such that the throughput is maximized. A flow rerouting approximation algorithm for the MCFP was introduced in (*19*) and also employed in (*20*). An extension of this algorithm in (*14*) was shown computationally to provide for the solution of much larger problems than could be solved by specialized linear programming codes (*21*). The use of the MCFP allowed for the model to be adapted from the simple four bridge network to the more complex network of the Charleston area.

2.3.3 *Traffic Network Effects*

The traffic network effects have been incorporated in optimization model based retrofit strategy designs, such as (*22-24*). Due to the large scale of traffic networks and the complexities in modeling the user equilibrium (UE) or system optimization (SO) traffic conditions (*25*), a compromised way to make the problem more tractable was to simplify retrofit decisions to be binary decisions (i.e., either retrofit a bridge or not), and the bridge damage conditions to be a binary situation that a bridge is either standing or collapsed. For example, Fan et al. (*22*) used binary retrofit decision variables and assumed binary bridge damage conditions in their optimization program for determining the best retrofit strategies for the highway bridges in the San Francisco Bay area under seismic hazards. The models in (*23, 24*) were similar to (*22*), in which, however, the UE rather than the SO traffic condition was assumed. Chang et al. (*26*) extended these assumptions to allow for a set of mutually exclusive retrofit alternatives and explicitly considered the probability of damage states in their study to maximize the post-disaster network evacuation capacity. However, they only budgeted for the retrofit cost and neglected the subsequent bridge damage cost resulting from the retrofit strategies.

2.4 Charleston's Infrastructure System

The Charleston region is composed of numerous towns, crossroad communities, as well as unincorporated rural areas. This allows for the region to offer many options to its residents in terms of residential locations and employment opportunities. From the historic downtown to the newer residential subdivisions, small rural communities, and beachfront towns, there are options for every lifestyle. Historic downtown Charleston, the natural amenities, and the beaches also make the region a popular tourist destination. Charleston is also a critical economic hub due to the Port of Charleston being one of the largest deep-water shipping ports and freight shipping centers in the US. However, the growth in employment, housing, shipping and tourism has resulted in increased traffic congestion that continues to worsen in major corridors.

2.4.1 *Highway Infrastructure*

Regional access in the region is provided by two important interstate highways and three major US Routes which are (See Figure 2.4):

- I-26 and I-526
- US 17, US 52, and US 78

I-26 is the one of the major interstate corridors in South Carolina. With connections from Johnson City, TN, Asheville, NC, and Columbia, SC, the corridor runs northwest/southeast through the state, terminating in Charleston, SC. At the western edge of the area, I-26 is a four-lane rural freeway. At the exit for US 17 Alternate, it becomes a six-lane freeway, which expands to eight lanes between Ashley Phosphate Road and I-526. This cross-section continues until the eastern terminus of the interstate at US 17 in Charleston. I-526 is a half-loop, four-lane facility that begins at US 17 west of the Ashley River and ends at US 17 in Mount Pleasant, providing connectivity to Daniel Island and North Charleston (*27*).

US 17 is a major US route that runs east/west across the region. It connects the Charleston peninsula with the mainland on both the east and the west. The newly constructed, eight-lane Arthur Ravenel Jr. bridge provides increased mobility and accessibility to and from US 17, the Charleston Peninsula, and I-26. US 52 and US 78 are also multilane major arterials that serve short as well as long distance travel (*27*).

Figure 2.4 Major Highway Map of Charleston, SC

The continuing growth in the Charleston region as well as limited mobility options has resulted in heavy congestion during peak hours on these major roadways. Due to limitations on design and by the geography, a lack of road connectivity is predominant creating morning and afternoon peak travel periods that have sections of commuter travel corridors frequently congested and can reduce to stop and go traffic.

The principal arterials within the Charleston area that are the most heavily congested include sections of I-26, I-526, and US 17. These roadways all have high volume/capacity (V/C) ratios, meaning they experience heavy traffic and long delays during peak hours. US 17 has a V/C ratio ranging from acceptable to well over capacity throughout much of the Charleston region, from I-526 in West Ashley through Mount Pleasant. I-26 and I-526 are two of the major traffic-carrying roads in the region, and currently both of these roads are operating near capacity, with V/C ratios generally between 0.8 and 1.0 (As the V/C approaches 1.0, the roadway becomes increasingly congested) (*27*). Although many of the main highway segments located near Charleston are in good condition in terms of a roadway standpoint they cannot handle the current and future vehicular demand.

Furthermore, critical areas (main components of the transportation system that need to be modified, i.e. capacity, maintenance, connectivity, etc..) have been identified by the Port Authority and trucking firms to be enhanced within the transportation infrastructure. The most predominant was the long term need to provide additional capacity for movements out of Charleston. Specifically these improvements would be needed on I-26 and I-526. While the trucking industry needs continue to grow along with the port, automobile traffic is still considered the major influencing factor, by transportation officials, on the necessity of roadway improvements. Possible solutions discussed include the widening of I-26 and the establishment of an alternative route. Transportation providers are in favor of the ongoing widening of a section of I-26 north of I-526. Although general concerns have been expressed that a much longer segment of

I-26 needs to be widened, potentially to Interstate 95 based on the anticipated impact of the Jedburg Commerce Park and adjacent proposed warehouse and transportation facilities. In addition, numerous freight providers indicated a need to rebuild the Interstate 26-Interstate 526 intersection to better handle freight transportation needs.

Other long-term needs include the improvement of the I-526/US 17 interchange to relieve traffic congestion and improve the traffic flow. Trucking firms have voiced support on several items including truck lane restrictions, keeping trucks to the two right-hand lanes, to try and help improve flow as well. Also, the concern of impatient drivers continually swerving in traffic has been raised. Recommendations to help alleviate this concern include signage and increased police patrolling along problematic corridors.

2.4.2 *Bridge Infrastructure*

Furthermore not only are the highway segments critical to transportation in Charleston, the bridges allowing these roadways are just as significant. According to the National Bridge Inventory (NBI) there are 281 bridges within the Charleston are that are annual assessed (*28*). Of the 281 bridges it was found that 32 are structurally deficient and 78 bridges are functionally obsolete. (Note: NBI does not include bridges being constructed or having major reconstruction within the last 10 years) Of the bridges located within the Charleston region 39% of the bridges are structural deficient or functionally obsolete, which is significantly higher than the national average of one in four bridges (25%) (*28*). According to the Federal Highway Administration (FWHA) bridges are considered structurally deficient (SD) if significant load carrying elements are found to be in poor condition due to deterioration and/or damage, or the adequacy of the waterway opening provided by the bridge is determined to be extremely insufficient to the point of causing overtopping with intolerable traffic interruptions. Examples of poor conditions include corrosion that has caused significant section loss of steel support members, movement of substructures, or advanced cracking and deterioration in concrete bridge decks. Bridges are considered functionally obsolete (FO) when the deck geometry, load carrying capacity (comparison of the original design load to the current state legal load), clearance, or approach roadway alignment no longer meet the usual criteria for the system of which it is an integral part (*29*). Functionally obsolete bridges are those that do not have adequate lane widths, shoulder widths, or vertical clearances to serve current traffic demand, or those that may be occasionally flooded. A functionally obsolete bridge is similar to an older house. A house built in 1950 might be perfectly acceptable to live in, but it does not meet all of today's building codes. Yet, when it comes time to consider upgrading that house or making improvements, the owner must look at ways to bring the structure up to current standards (*28*).

2.4.3 *Impacts of Natural Disasters*

The main threat to Charleston's infrastructure comes from nature itself in natural disasters. From historical data, the natural disasters to be most likely to affect Charleston are severe storms, earthquakes, flooding, and tornadoes. The most memorable of these disasters being Hurricane Hugo in 1989 and the Charleston earthquake of 1886. Hugo caused for much of the infrastructure within Charleston to be damaged or destroyed due to high winds and severe flooding. Sullivan's Island and Isle of Palms were both cut off from the mainland as the only bridge leading to the islands was destroyed. Many other roads and bridges were flooded or under water due to the low elevation of the Charleston area. The limited connectivity of the roads in Charleston and the further limiting of areas due to flooding caused this to become a severe problem. Economic damages in South Carolina alone are estimated to be $10.5 billion (*30*). Due to Charleston's economic status these damages were especially high within the region. This storm, however, was limited in the loss of life due to evacuations. Without a competent infrastructure system these evacuations would not be possible. If these systems are not kept up or updated to a certain standard the losses caused from natural disasters could be even worse.

In addition, Charleston is the site of one of the strongest earthquakes to hit the eastern seaboard of the United States. The earthquake occurred in 1886 and registered with an approximate magnitude of 7 on the Richter scale. This event caused for more deaths, injuries, and property damage than Hurricane Hugo. Sixty-seven percent of Charleston's brick buildings were destroyed including its three main medical facilities. The damages seen to Charleston alone were estimated to be $281 to $338 million in terms of 2012 dollars (*31*). Although this event happened over 120 years ago, due to its occurrence it has been theorized it will happen again. Using the FEMA provided program of HAZUS (estimates potential losses from natural disasters) studies have been done to model this situation if it were to happen again. From the results they found that economic loss from the Charleston region would be over $14 billion (77% of the total), and many bridges would be damaged to the point they would no longer be usable cutting off portions of Charleston only accessible by bridges (*32*). Extensive damage to both buildings and infrastructure, such as roads, bridges, and railroads, would also been seen.

Although these are examples of extreme cases, the possibilities of damages to infrastructure, the economic losses, and its importance to safety is easily seen.

2.4.4 *Seismic Risk Assessment of Charleston, SC*

Regional seismic risk assessments (SRAs) are becoming popular tools for evaluating the performance of transportation networks under earthquake loading. The term *seismic risk* refers to the potential for damage or losses that may be associated with a seismic event. Such regional assessments provide a unique approach for estimating the risk to highway infrastructure by evaluating potential bridge damage and consequences of the seismic event, such as the estimated direct and indirect losses (*33*). This framework offers support to decision-makers for pre-event planning and risk mitigation, emergency route identification, retrofit selection and prioritization (*33*).

Methodologies for seismic risk assessment of transportation systems have been presented by many researchers in the field of lifeline earthquake engineering (*34, 35, 36, 37*). These methodologies offer a potential framework for assessing likely bridge damage, direct losses due to repair and replacement of the structures, and some extend this evaluation to include an assessment of the impact of the event on network performance and the resulting indirect economic losses (*38, 39*)

In a risk assessment of the Charleston area conducted by Padgett, Desroches, and Nilsson (*33*), 375 bridges were assessed using bridge fragility curves representative of the unique characteristics of the bridges in the region. In addition to the use of state-specific bridge repair and replacement cost data for damage and loss estimation. The risk assessment was conducted for three different scenario events as defined with recommendations from the South Carolina Department of Transportation (SCDOT), earthquakes of magnitude M_W 4.0, 5.5, and 7.0 located at 32.9° N, 80.0° W. This location was the same point at which the Charleston earthquake of 1886 originated. The case study revealed expected damage states of moderate, extensive, or complete damage for over 85% of the Charleston bridges due to a M_W 7.0 event (*33*).

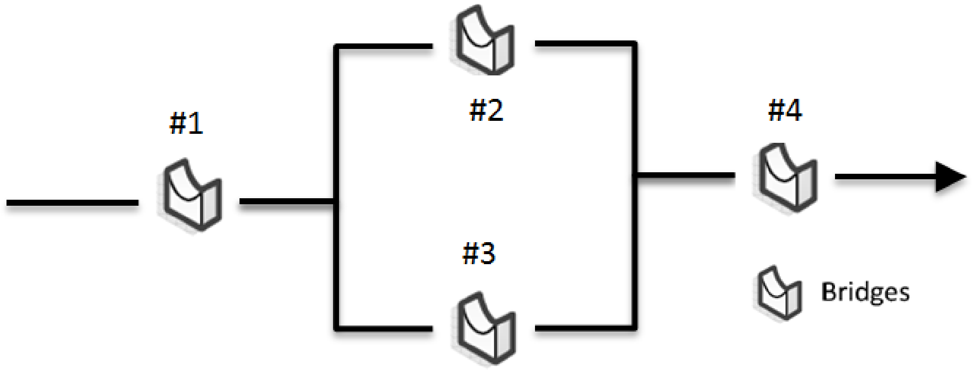
2.4.5 *Economic Importance*

Moreover, the Port of Charleston is an economic gateway employing one of the largest groups of people in the region as well as the state. The impacts and jobs associated with freight extends beyond the port facilities, including those employed by trucking firms, warehouses, railroads, and other intermodal facilities, as well as services associated with these businesses. As of 2008 nearly 9,000 people were employed in the transportation and warehousing sector with the majority in port related activities. Freight transportation along with regional tourism is a major driving force for Charleston economy, and affects an estimated 261,000 jobs in South Carolina alone (*27*). With a continually expanding region depending directly on these transportation facilities stated (highways and bridges) a critical need arises to keep these facilities up to date and in good condition. If this is not completed a significant impact to both South Carolina's and the United States' economy will be seen.

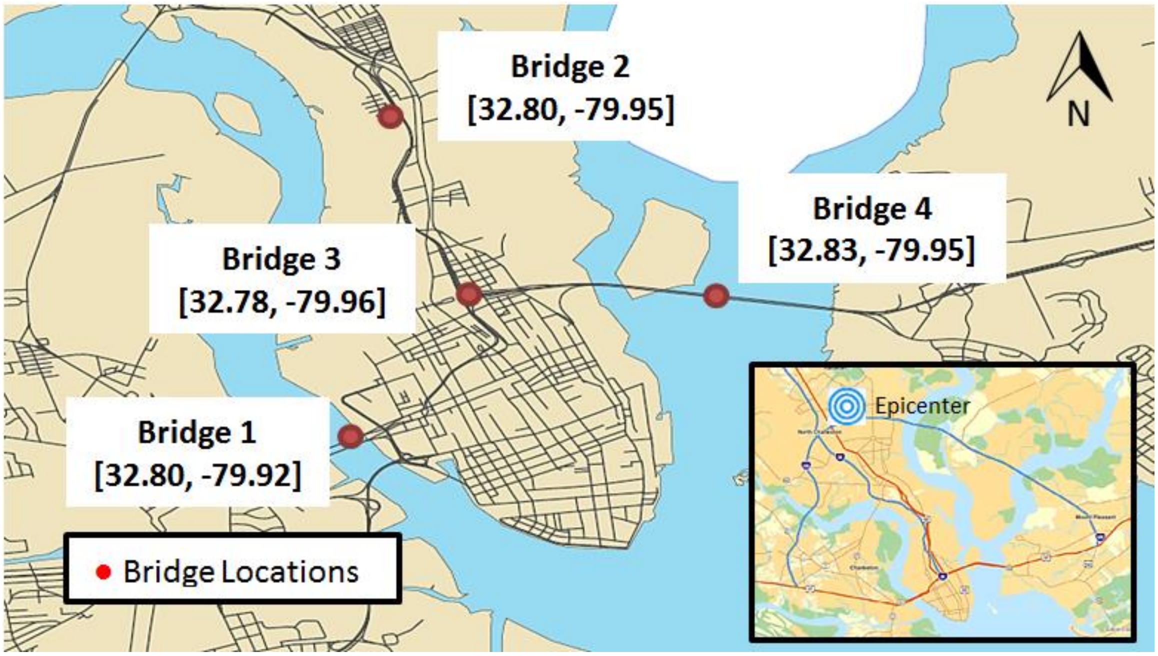
CHAPTER THREE

MODEL FORMULATION

This research developed an optimization program to determine the best bridge retrofit strategies, with the lowest total expenditures on retrofitting the desired bridges and the subsequent expected damage cost. A simplified four-bridge network was used, using bridges representative of the Charleston area to illustrate the optimization model. The geographic information system (GIS) map based on the data from the South Carolina DOT (*40*) is shown in Figure . Figure 3.1(a) shows the simple bridge network used for the model demonstration. The bridges #1 and #4 are in series and the bridges #2 and #3 are in parallel. Figure 3.1(b) shows the four bridges chosen along the major highways in the Charleston area and labeled with the latitudes and longitudes. It is assumed that the four bridges are independent from each other, meaning that damage to one bridge would not affect the others.



(a) **Four-Bridge Sample Network**



(b) **GIS Map of Charleston Area.**

Figure 3.1 A Simplified Charleston Area Transportation Network

In this research, the probability of a bridge experiencing a damage state $d \in D$ (where D denotes the set of aforementioned possible damage states) relates to the geographic location $i \in I$ (where I denotes the set of bridges in the network, i.e., bridges #1, 2, 3, and 4 in this sample network) and the retrofit strategy $s \in S$ (where S denotes the set of aforementioned possible retrofitting strategies). The probability of bridge i

with retrofit *s* experiencing damage state *d* under an earthquake scenario is denoted as $P_{d,i,s}$. Scenario-based seismic analysis was used, a method selecting one or a limited set of scenario earthquakes for analysis (*41*). The selection is focused on the largest (magnitude) earthquakes, called maximum credible earthquakes (MCEs), expected from each source (*41*).

It is challenging to estimate the actual retrofitting cost. In this research, it was assumed that the retrofitting cost is as a percentage (denoted as $\hat{\rho}_s$) of the new construction cost (denoted as CR_i). It was further assumed that the bridge damage cost due to the seismic hazards is linearly proportional to the capacity loss (1- ρ_d) where ρ_d is the remaining capacity of a bridge after an earthquake. The assumed bridge remaining traffic capacities (ρ_d) under damage states d0 through d4 are respectively 1, 0.8, 0.6, 0.2, and 0 of the original traffic capacity.

A mixed integer linear programming model was formulated to minimize the total cost of retrofitting bridges and the expected damage cost while meeting a prescribed system-level traffic capacity. The model will explicitly determine retrofit strategies on the network of bridges. The complete model is given in (3.1)-(3.5).

Minimize
$$\sum_{i\in I}\sum_{s\in S} CR_i X_{i,s}\hat{\rho}_s + \sum_{d\in D}\sum_{i\in I}\sum_{s\in S}(1-\rho_d)CR_i P_{d,i,s} X_{i,s} \tag{3.1}$$

Subject to

$$C_i \sum_{d\in D}\sum_{s\in S} P_{d,i,s}\rho_d X_{i,s} \geq cap\,, \forall i = 1,4 \tag{3.2}$$

$$\sum_{i=2,3}\sum_{d\in D}\sum_{s\in S} C_i P_{d,i,s}\rho_d X_{i,s} \geq cap \tag{3.3}$$

$$\sum_{s \in S} X_{i,s} = 1, \ \forall i \in I \tag{3.4}$$

$$X_{i,s} \in \{0,1\}, \ \forall i \in I, s \in S \tag{3.5}$$

Sets:

I: index i, set of bridges in the network,

S: index s, set of available retrofit strategies,

D: index d, set of possible damage states,

Parameters:

CR_i: the new construction cost ($) of bridge $i \in I$,

C_i: traffic capacity of bridge (veh/day) $i \in I$,

ρ_d: the percent of remaining traffic capacity under damage state $d \in D$,

$\hat{\rho}_s$: the percent of the replacement cost as a new construction of a bridge when retrofit strategy $s \in S$ is applied,

$P_{d,i,s}$: Probability of damage state $d \in D$ occurs at bridge i under retrofit strategy $s \in S$,

cap: the designed through-traffic capacity of the network (veh/day).

Decision Variables:

$X_{i,s} = 1$ if retrofitting strategy s is selected for bridge i; 0 otherwise.

The objective (3.1) is to minimize the total system cost including the *expenditures on retrofits* in the first term and the *expected damage costs* in the second term. The retrofit decisions are made prior to an earthquake and the subsequent damage cost are evaluated in the aftermath of an earthquake. Constraints (3.2) and (3.3) require the post-disaster capacity of the transportation network to meet a prescribed capacity level, measured by the average daily traffic (ADT). These two constraints are dependent on the network topology. For this particular four-bridge network, constraint (3.2) is imposed individually on the bridges #1 and #4 which are in series and the capacity of either of the bridges should not be lower than the capacity level. Constraint (3.3) is for the bridges #2 and #3 in parallel and it requires the total capacity of them to be no less than the capacity level. Constraint (3.4) states that only one retrofit strategy can be applied to a bridge. The retrofit decision variable is defined in constraint (3.5).

3.1 Data Description

HAZUS uses GIS technology to estimate physical, economic, and social impacts of disasters. It graphically illustrates the limits of identified high-risk locations due to earthquakes, hurricanes, and floods (*23*). The seismic fragility curves and bridge classification data, located within HAZUS, are based on the National Bridge Inventory (NBI) data. This classification scheme incorporates various parameters that affect damage into fragility analysis and provides a means to obtain fragility curves that are location specific, allowing the probability of each damage state to be found and used within the model. A total of 28 classes are defined this way helping differentiate between the different bridge characteristics found in the NBI. The HAZUS software was used to model the aforementioned earthquake event and determine its impacts on the bridge network in terms of the *probability* of each damage state and the *replacement cost* for each bridge. The most notable 1886 Charleston earthquake (originated at 32.9°N, 80.0°W with a magnitude of 7.0 M_L) was used as the earthquake scenario. Since it relates to the worst-case scenario, it ensures that the bridge network will receive damage that needs to be mitigated by the model (*42*). The latitudes and longitudes of the bridges (see Figure 3.1(b)) help retrieve the probabilities of damage states and new construction cost for each bridge from the HAZUS program.

The probabilities adopted from HAZUS program represent the “do nothing” (S0) retrofit alternative. These probabilities were then modified to represent the probabilities of each damage state when a retrofit strategy other than “do-nothing” is applied, i.e., S1, S2, S3, and S4. In this research, it is assumed 10%, 15%, 20%, and 25% reductions in the risk if a bridge respectively takes retrofit strategies S1, S2, S3, and S4 and thus the corresponding probabilities are 90%, 85%, 80%, and 75% of their respective probabilities of strategy S0, i.e., $P_{d,i,1} = 90\% P_{d,i,0}$, $P_{d,i,2} = 85\% P_{d,i,0}$, $P_{d,i,3} = 80\% P_{d,i,0}$, and $P_{d,i,4} = 75\% P_{d,i,0}$, $d \in D$, $i \in I$. The probabilities of damage states of the four bridges resulted from using retrofit strategies S0-S4 are displayed in Table 3.1. For example, for bridge #1, the probability of being minor damage (d1) is 0.073 or 7.3% if retrofit strategy doing nothing (S0) is selected and the probability reduces to 0.0657 (i.e., 90% of 0.073) if the enhanced retrofit strategy (S1) is applied. Note for each strategy, the summation of probabilities over the five damage states (i.e., d0-d4) equals one. The probability of no damage (i.e., d0) increases with higher retrofit strategies (rows of “d0” in the table) while the probabilities of the other damage states decrease (other rows).

Table 3.1 Probabilities of Damage States for Four Bridges by Using Retrofit Strategies

Bridges	*Damage states*	*Do Nothing (S0)*	*Superstructure (S1)*	*Superstructure & Substructure (S2)*	*Superstructure, Substructure, & Foundation (S3)*	*Complete Replacement (S4)*
#1	None (d0)	0.085	0.1765	0.22225	0.268	0.31375
	Minor (d1)	0.073	0.0657	0.06205	0.0584	0.05475
	Moderate (d2)	0.171	0.1539	0.14535	0.1368	0.12825
	Extensive (d3)	0.162	0.1458	0.1377	0.1296	0.1215
	Complete (d4)	0.509	0.4581	0.43265	0.4072	0.38175
#2	None (d0)	0.009	0.1081	0.15765	0.2072	0.25675
	Minor (d1)	0.026	0.0234	0.0221	0.0208	0.0195
	Moderate (d2)	0.047	0.0423	0.03995	0.0376	0.03525
	Extensive (d3)	0.173	0.1557	0.14705	0.1384	0.12975
	Complete (d4)	0.745	0.6705	0.63325	0.596	0.55875
#3	None (d0)	0.396	0.4879	0.51635	0.5448	0.57325
	Minor (d1)	0.147	0.1323	0.12495	0.1176	0.11025
	Moderate (d2)	0.117	0.1053	0.09945	0.0936	0.08775
	Extensive (d3)	0.18	0.162	0.153	0.144	0.135
	Complete (d4)	0.125	0.1125	0.10625	0.1	0.09375
#4	None (d0)	0.004	0.1036	0.1534	0.2032	0.253
	Minor (d1)	0.014	0.0126	0.0119	0.0112	0.0105
	Moderate (d2)	0.028	0.0252	0.0238	0.0224	0.021
	Extensive (d3)	0.125	0.1125	0.10625	0.1	0.09375
	Complete (d4)	0.829	0.7461	0.70465	0.6632	0.62175

Table 3.2 Cost of Retrofit Strategies as Percentage of New Construction Costs ($\hat{\rho}_s$)*

Range	*Retrofit Strategies*		
	Superstructure Only (S1)	Superstructure and Substructure (S2)	Superstructure, Substructure and Foundations (S3)
Low	1.3	0.7	2.3
Average	3.1	15.4	28.8
High	13.2	64.8	232.9

* adapted from (*1*)

Table 3.3 Critical Parameters of Bridges

Bridges	*Replacement Cost ($m)**	*Traffic Capacity (Veh/Day)*
#1	56.7	50,000
#2	76.4	30,000
#3	9.5	20,000
#4	8.4	50,000

* adapted from HAZUS program

The estimate of actual cost of retrofitting bridges is challenging as very few states have completed extensive retrofit programs, from which to take data. The Federal Highway Administration (FHWA) has complied data based on California Department of Transportation experience in retrofitting 165 bridges during 1993 and 1994 in Table 3.2. The costs are expressed as percentages of new construction for same time frame and the low, average, and high ranges of estimates are provided. In this research, the "average" retrofit cost range is used due to South Carolina's lower seismic risk when compared to California. When the superstructure is retrofitted (corresponding to the retrofit strategy S1 in this study) the average cost is 3.1% of new construction cost. When the substructure is also considered along with the superstructure (i.e., strategy S2) the average cost increases to 15.4 percent. Finally, when the foundation, super, and substructures (i.e., strategy S3) are all included the average price increases further to 28.8 percent. The cost of strategy S0 is zero and the strategy S4 costs as much as the new construction of a bridge. An enhanced strategy normally costs more. The new construction cost for each of the bridges adopted from HAZUS is summarized in Table 3.3, which is relevant to their geographic locations. With this information, the retrofit cost can be estimated. For example, when the strategy S1 is applied to bridge #1, it costs \$1.76m (=\$56.7m $\times$3.1%). The assumed traffic capacity of each bridge and the geographic location information of the bridges are also reported in Table 3.3.

3.2 Numerical Solution and Analysis

The optimization model is developed to produce the optimal retrofit strategies for the bridges in the network. The retrofit solutions will be different in response to different traffic capacity levels, which in reality are normally identified by the DOTs as targets.

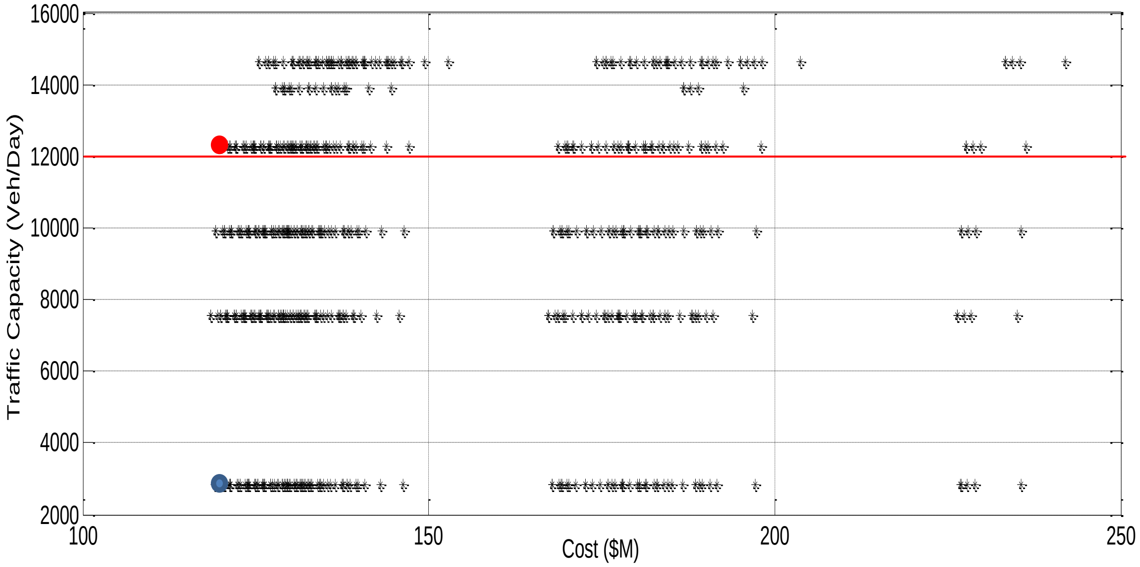


Figure 3.2 Results of All Possible Solutions of Retrofit Strategies

Before solving the optimization model, the performances of all possible combinations of the five retrofit strategies applied to the four bridges were evaluated and the resulted 1024 (= 4^5) different solutions are plotted in Figure 3.2, in which the horizontal and vertical axes respectively represent the total cost in millions of dollars ($m) and traffic capacity in vehicles per day (veh/day). In this research, a feasible solution is any solution that satisfies all constraints within the model while the optimal solution satisfies both the objective and all constraints. The results indicate that the network can support a traffic throughput of up to 14,638 veh/day. Given a particular capacity target, say 12,000 veh/day, feasible solutions are easy to identify, which are the ones above the horizontal line of 12,000 (in red) and the ones below the line will be disregarded, since they cannot satisfy the traffic capacity requirements. Within the feasible solutions, the most economical retrofit solution is represented by the dot above the line on the most left as highlighted. In addition, the results in the figure also show the minimum traffic capacity at 2850 veh/day, a result of the strategy of “do nothing” (S0). However, as noted, it is not the most economical solution, since both the retrofit and damage costs are included in the objective and the resulted high damage cost (i.e., $121.4m) has made the total cost compromised.

The stepwise shaped results in the figure suggest that for a particular traffic capacity the solution represented by the dot on the most left of the line is the most economical and will be considered. All the other dots on the same line will be disregarded due to the higher costs. Thus, there is a significant computing waste on generating unused solutions. This is caused by the retrofitting of non-critical bridges. For example, if bridge #1 is the weakest in the bridge set and determines the traffic throughput. There are still 243 (=3^5) combinations of solutions that do not include the retrofitting of bridge #1. This leads to the possible traffic throughput of the network to remain constant while the cost increases. In addition, for a real-world network, it is unrealistic to enumerate all possible retrofit solutions. With these, it is easy to justify the use of the optimization model for the best retrofit solutions. However, these solutions generated in Figure 3.2 will be used to validate the solutions of the optimization model.

The optimization model was programed using AMPL (*43*) and solved by the commercial optimization solver CPLEX12.4. Six different traffic capacities were assumed as the model inputs according to the results in Figure 3.2Figure , which are 2,000, 7,000, 9,000, 12,000, 13,000, and 14,000 veh/day. The model was ran separately for each of the six traffic capacity levels and the corresponding retrofit solutions and the resulting costs are displayed in Table 3.4. The optimal retrofit strategies vary with traffic capacities. Barely meeting the minimum capacity requirement does not guarantee the most economical solution in terms of the total retrofit and damage cost. For example, when the traffic capacity is required at merely 2,000 veh/day, the model suggests the strategy S1 to all the four bridges, although the strategy S0 can already provide 2850 veh/day to the network as shown in Figure 3.2. The reason is the total cost of $113.95m resulted from S1 beats off the high expected damage cost of $121.4m by S0. This also justifies the use of both the retrofit and damage costs. As the traffic capacity increases, enhanced retrofit strategies are used. When it is as high as 14,000 veh/day, the bridge #4 needs the strategy S4. Additionally, the bridge #4 is identified as the bottleneck to the network, mainly due to the high failure probability that makes the bridge most susceptible to damage. The solutions in Table 3.4 were verified by comparing them with the solutions in Figure 3.2. It can be seen that the optimization solutions correspond to the most left dots in the figure. This solution set is called a solution (P).

Table 3.4 Optimal Retrofit Strategies for Bridges and Associated Costs for Various Traffic Capacity Levels

Traffic Capacity (Veh/Day)	*Bridge 1*	*Bridge 2*	*Bridge 3*	*Bridge 4*	*Retrofit cost ($m)*	*Expected damage cost ($m)*	*Total Cost ($m)*
2,000	S1	S1	S1	S1	4.68	109.28	113.95
7,000	S1	S1	S1	S1	4.68	109.28	113.95
9,000	S1	S1	S1	S2	5.71	108.88	114.59
12,000	S1	S1	S1	S3	6.84	108.48	115.32
13,000	S1	S1	S1	S4	12.83	108.09	120.92
14,000	S1	S1	S1	S4	12.83	108.09	120.92

CHAPTER FOUR

APPLICATION TO CHARLESTON NETWORK

4.1 Formulation for Charleston Transportation Network

The developed model from Chapter 3 was extended for the use in a real-world application in the Charleston area. In particular, this research effort aims to provide timely and sufficient aid to downtown Charleston in an event of earthquake. Although this research focuses on sending rescue resources into downtown Charleston, the model developed can additionally be used to model an evacuation scenario by simply reversing the traffic flows in the network.

Through researching the Charleston area, the routes most crucial for access to the region were found to be two interstate highways (I-26 and I-526) and three major US Routes (US 17, US 52, and US 78). These routes became the basis for the setup of the transportation network (Figure 2.4).

Using the National Bridge Inventory (NBI) data for the state of South Carolina provided from the HAZUS program, bridges were first filtered by county to limit the case study to the area of interest in Charleston, South Carolina. They were then filtered again by their location only selecting those that fell along the major highways. Bridges were selected not only by their location on the major routes but by their traffic volume on the route. For this research it was assumed that bridges with traffic volumes under 5000 veh/day (AADT) were not considered to be significant and are not included in the model. This yielded an inventory of 79 bridges along the major routes, described above, to be evaluated in the model (Figure 4.1).

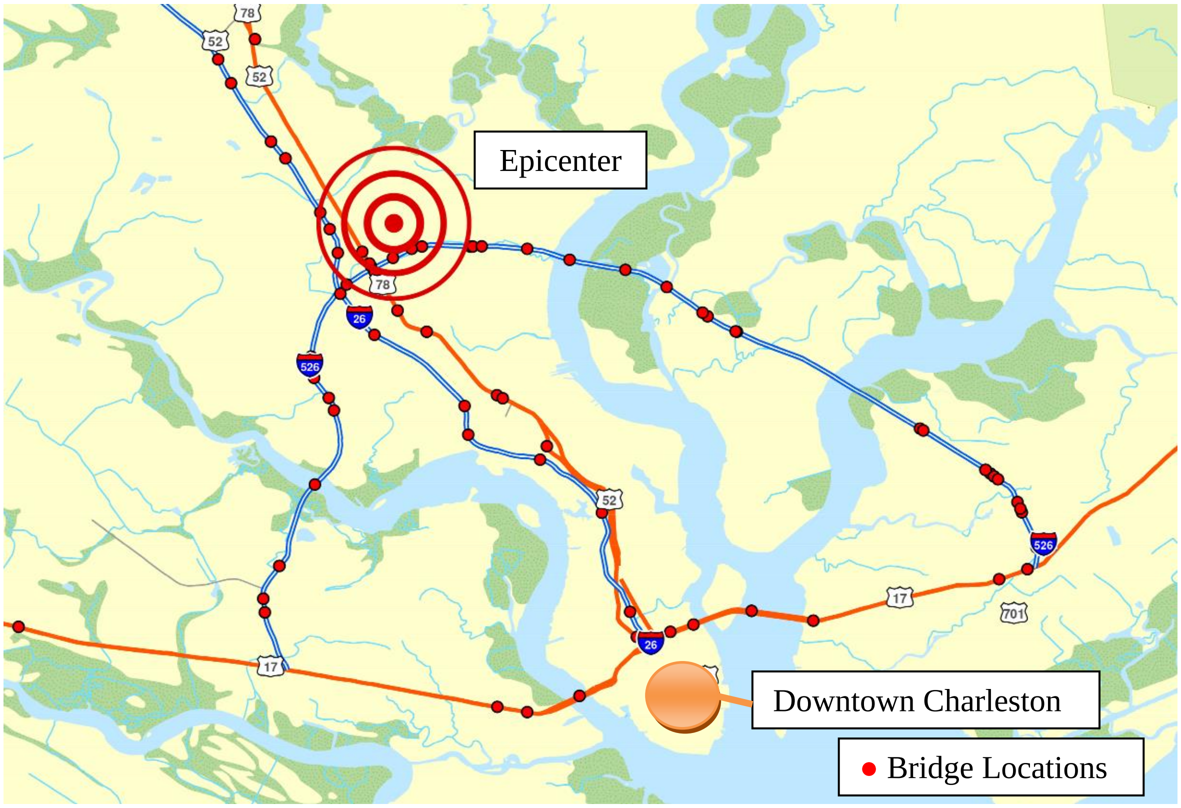


Figure 4.1 Charleston Area Bridges Considered

To adapt the model to Charleston area, the modeling network framework had to be defined. For the network, the locations at which two highways intersect were considered to be the nodes, while the roadways containing the bridges were considered to be the links of the network. External flows were considered along all major interstates into downtown Charleston. Thus, four origins were set for the external flows along the major highways as they enter the Charleston and a single destination set as downtown Charleston. External flows were considered to originate along I-26 South, US 17 West and East, and US 52 South. The model allows for external flow from all four origins to be considered concurrently. The bridges on a given link were grouped and considered to be in series. The nodes are labeled from 1 to 11 with 11 being the destination and nodes

1-4 being the origins of the network. The bridge groups consist of 12 groups, denoted as E,Q,C,K,G,J,H,N,P,L,O,M (See Figure 4.2). It was also assumed that the bridges are independent from each other, meaning that damage to one bridge would not affect the others.

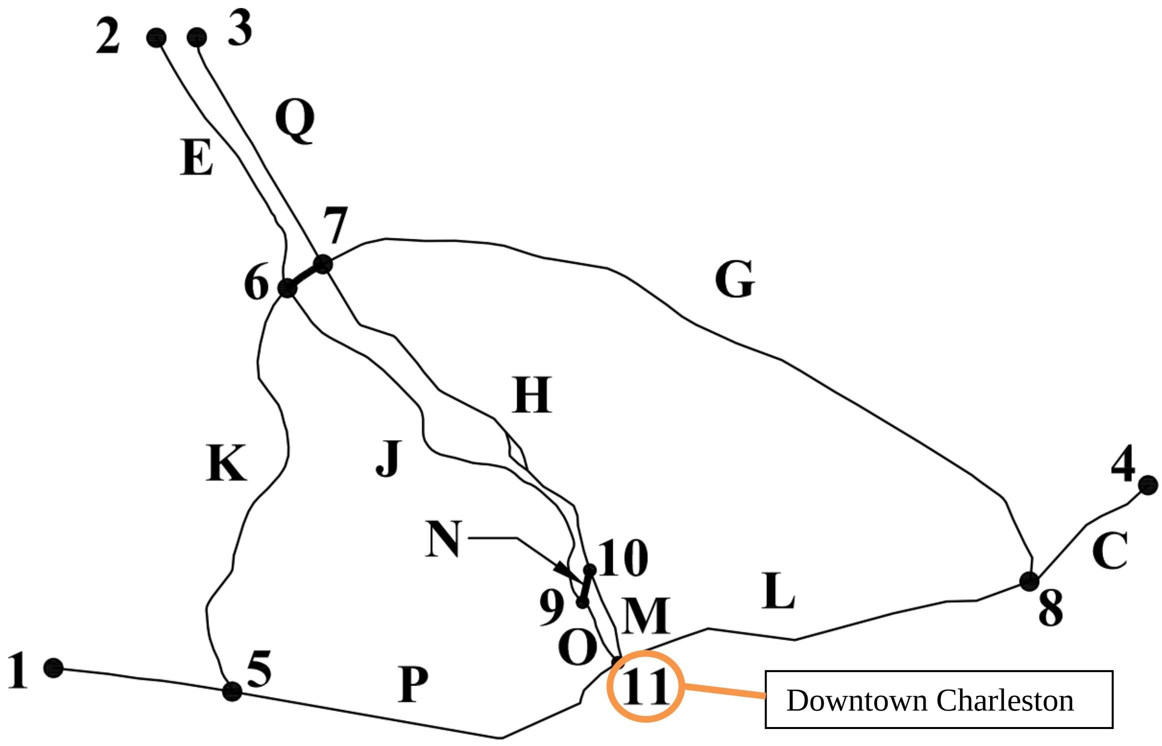


Figure 4.2 Charleston Modeling Network

A mixed integer linear programming model, a variant of the model in Chapter 3 designed for this comprehensive bridge network, was formulated to minimize the total cost of retrofitting bridges and the expected damage cost while meeting a prescribed external flows (i.e., desired flow in the formulation) entering the network through the four origins. The model will explicitly determine retrofit strategies on the network of bridges. The complete model is given in (4.1)-(4.24).

Minimize $$\sum_{i\in I}\sum_{s\in S} CR_i X_{i,s}\hat{\rho}_s + \sum_{d\in D}\sum_{i\in I}\sum_{s\in S}(1-\rho_d)CR_i P_{d,i,s}X_{i,s} \tag{4.1}$$

Subject to:

$$F_{0,1}+F_{0,2}+F_{0,3}+F_{0,4} \geq \text{"}desired\_flow\text{"} \tag{4.2}$$

$$F_{0,1}=F_{1,5}\leq 2C_{1,5} \tag{4.3}$$

$$F_{0,2}=F_{2,6}\leq 2C_{2,6} \tag{4.4}$$

$$F_{0,3}=F_{3,7}\leq 2C_{3,7} \tag{4.5}$$

$$F_{0,4}=F_{4,8}\leq 2C_{4,8} \tag{4.6}$$

$$F_{1,5}+F_{6,5}=F_{5,11}\leq 2C_{5,11} \tag{4.7}$$

$$F_{2,6}+F_{7,6}=F_{6,5}+F_{6,9}+F_{6,7} \tag{4.8}$$

$$F_{3,7}+F_{6,7}=F_{7,8}+F_{7,10} \tag{4.9}$$

$$F_{4,8}+F_{7,8}=F_{8,11}\leq 2C_{8,11} \tag{4.10}$$

$$F_{10,9}+F_{6,9}=F_{9,11}+F_{9,10} \tag{4.11}$$

$$F_{7,10}+F_{9,10}=F_{10,9}+F_{10,11} \tag{4.12}$$

$$F_{5,11}+F_{9,11}+F_{10,11}+F_{8,11} \geq \text{"}desired\_flow\text{"} \tag{4.13}$$

$$F_{6,5}\leq 2C_{6,5} \tag{4.14}$$

$$F_{6,9}\leq 2C_{6,9} \tag{4.15}$$

$$F_{7,10}\leq 2C_{7,10} \tag{4.16}$$

$$F_{7,8}\leq 2C_{7,8} \tag{4.17}$$

$$F_{6,7},F_{7,6}\leq C_{6,7} \tag{4.18}$$

$$F_{9,10}, F_{10,9} \le C_{9,10} \tag{4.19}$$

$$F_{9,11} \le 2C_{9,11} \tag{4.20}$$

$$F_{10,11} \le 2C_{10,11} \tag{4.21}$$

$$C_{a,b} = C_i \sum_{d \in D} \sum_{s \in S} P_{d,i,s} \rho_d X_{i,s} \qquad \forall i \in E, Q, C, K, G, J, H, N, P, L, O, M \tag{4.22}$$

$$\sum_{s \in S} X_{i,s} = 1 \qquad \forall i \in I \tag{4.23}$$

$$X_{i,s} \in \{0,1\} \qquad \forall i \in I, s \in S \tag{4.24}$$

Sets:

I,E,Q,C,K,G,J,H,N,P,L,O,M: index *i*, set of bridges in the network,

S: index *s*, set of candidate retrofit strategies,

D: index *d*, set of possible damage states,

A: index a, set of origin nodes in the network,

B: index b, set of destination nodes in the network,

Parameters:

$F_{a,b}$: flow from node $a \in A$ to node $b \in B$,

CR_i: replacement cost of bridge at $i \in I$,

C_i: capacity for bridge $i \in I$,

$C_{a,b}$: maximum capacity of link from node $a \in A$ to node $b \in B$,

ρ_d : the percent of capacity lost under damage state $d \in D$,

$\hat{\rho}_s$: the percent of the replacement cost when retrofitting strategy $s \in S$ is applied,

$P_{d,i,s}$: probability of damage state $d \in D$ occurs at bridge *i* under retrofitting strategy $s \in S$

desired_flow: the total desired throughput-traffic of the network.

Decision Variables:

$X_{i,s}$ = 1 if retrofitting strategy *s* is selected for bridge *i*; 0 otherwise

The objective (4.1) is to minimize the total system cost including the *expenditures on retrofits* in the first term and the *expected damage costs* in the second term. The retrofit decisions are made prior to an earthquake and the subsequent damage cost are evaluated in the aftermath of an earthquake. Constraints (4.2)-(4.21) represent the flow conservation and capacity of links in the network. Constraint (4.22) evaluates the traffic capacity of the bridges on each link of the network, measured by traffic flow rate (veh/hr). Constraint (4.23) states that only one retrofit strategy can be applied to a bridge. The retrofit decision variable is defined in constraint (4.24).

4.2 Data Description

The same datasets were prepared for this Charleston bridge network. This includes using HAZUS to determine the probability of each damage state and replacement cost for each bridge, the reductions to damage state probabilities from each retrofit, and the retrofit cost being a percentage of the replacement cost (See Appendix A). In particular, as determined in (*33*) according to the recommendations by the SCDOT, earthquakes of magnitude (M_W) 5.5 and 7.0 located at 32.9° N, 80.0° W were selected to evaluate the bridge network. The traffic capacity for the 79 bridges was not available, and thus was estimated using the Highway Capacity Manual (HCM)

Procedures for Estimating Highway Capacity (*44*) with the bridge dimensions provided from the HAZUS program. The procedures are described as follows and detailed calculations for each bridge are available in Appendix B.

1. Calculate Free Flow Speed (FFS)

   The first step in the procedure is to estimate free flow speed (FFS) using the Highway Capacity Manual's equation 23-1: $FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}$. The base free flow speed was assumed to be the speed limit of the roadway and such speed will be adjusted according to the reduction factors of the roadways, which are lane width, number of lanes, shoulder width, and interchange density, respectively. The data used to assign the adjustment factors, through tables provided in the highway capacity manual, were found using the information provided in the HAZUS dataset or through the use of the GIS software ArcGIS.

2. Calculate Base Capacity (Base Cap)

   The base capacity (passenger cars per hour per lane) of a freeway facility is based on the following equations developed from information found in the *HCM* Exhibit 23-3.

   $BaseCap = 1{,}700 + 10FFS$; for FFS <= 70

   $BaseCap = 2{,}400$; for FFS > 70

3. Determine Peak Capacity (Peak Cap)

The final step in the procedure is to make adjustments to the base capacity. These adjustments convert the units from passenger cars equivalents to vehicles and lower capacity to account for the effect of heavy vehicles. The procedure is based on *HCM* equation 23-2: $PeakCap = BaseCap * PHF * N * f_{HV} * f_p$. The base capacity found in the previous step is adjusted according to the peak hour factor, the number of lanes in one direction, and adjustment factors for both heavy vehicles and the driver population. The peak hour factor was 0.92 and the adjustment for the driver population was 1 as recommend in the Highway Capacity Manual for urban areas. The adjustment for heavy vehicles was assumed to be 1 as the model was finding the ability for aid vehicles to traverse the network and not normal traffic.

4.3 Numerical Solution and Analysis

The optimization model was programed using AMPL (*43*) and solved by the commercial optimization solver CPLEX12.4. A complete AMPL programming code is attached in Appendix C. Before the model was implemented, a baseline was established for the potential damage associated with both the M_W 5.5 and M_W 7.0 events. Having this baseline will allow for the results from the model to be compared in terms of total system cost and validate the retrofitting strategies chosen by the model. Additionally, it demonstrates the need for retrofitting if the chosen earthquake events were to happen and the benefits that can be achieved. Using the results from the HAZUS program (Table 4.1) it was found that for the M_W 5.5 event the expected damage cost is approximately

$142 million with an associated system traffic capacity of 14,377 veh/hr. It is expected that 40% of the bridges in the study area will receive slight, moderate, extensive, or complete damage. For the M_W 7.0 event, the expected damage cost is approximately $369 million with an associated system traffic capacity of 2,411 veh/hr. With this extreme event, 42% of the bridges would be receiving slight, moderate, or extensive damages, while 40% of bridges are expected to fail completely. Meaning that in the case the Charleston earthquake of 1886 was to be repeated, 82% of the bridges in the area would be damaged if no retrofitting was put in place.

Table 4.1 Baseline of Potential Damage to the Charleston Area

	Earthquake Event	
	M_W 5.5	M_W 7.0
Damage State	*Percent of Bridges (%)*	*Percent of Bridges (%)*
None	60	18
Slight	12	11
Moderate	8	11
Extensive	11	20
Complete	9	40

After implementing the model on the Charleston network, the maximum throughput that can be achieved through retrofitting and the associated total system cost were found for both the M_W 5.5 and M_W 7.0 earthquake events. By applying the maximum amount retrofitting at the lowest cost, the maximum traffic throughput the network is capable of handling for the M_W 5.5 event was found to be 20,841 veh/hr with an associated cost (using the average cost range) of $153 million. For the M_W 7.0 event, the maximum throughput was found to be much lower at 11,828 veh/hr with an associated system cost of $381 million.

In addition to the maximum throughput traffic capacities, five other different levels of throughput traffic capacities were assumed to create a full spectrum of desired flows of sending emergency aid into the downtown Charleston in the case of extreme events, which are 14,377, 15,000, 16,500, 18,000, 19,500 veh/hr for the M_W 5.5 event, and 2,411, 4,000, 6,000, 8,000, and 10,000 veh/hr for the M_W 7.0 event. The chosen traffic throughput levels were different for each event due to the differing levels of expected damage the network was to receive. The M_W 5.5 event will, of course, have less damage to the bridges within the network, and the traffic throughput levels chosen for the M_W 7.0 event may not be significant when applied. The chosen throughput levels ensure the model demonstrates its ability to mitigate damage while meeting the throughput at a variety of levels. The model was ran separately for each of the six traffic capacity levels and the resulting retrofitting costs, expected damage costs, and total cost are displayed in Tables 4.2 and 4.3 for M_W 5.5 and M_W 7.0 earthquake events, respectively. The complete optimal retrofit solutions for both the M_W 5.5 and M_W 7.0 earthquake events for each of the 79 bridges of study are provided in Appendix D. The solution set for the “average cost” range is referred to herein as solution (P).

Table 4.2 Optimal Retrofit Strategies for Bridges and Associated Costs for Various Traffic Capacity Levels for M_W 5.5 Event

Desired Throughput (Veh/Hr)	*Retrofit cost ($m)*	*Expected damage cost ($m)*	*Total Cost ($m)*
14377	3.59	134.82	138.41
15000	3.59	134.82	138.41
16500	3.59	134.82	138.41
18000	4.19	134.69	138.88
19500	7.14	134.04	141.18
20841	20.52	132.50	153.03

Table 4.3 Optimal Retrofit Strategies for Bridges and Associated Costs for Various Traffic Capacity Levels for M_W 7.0 Event

Desired Throughput (Veh/Hr)	*Retrofit Cost ($m)*	*Expected damage cost ($m)*	*Total Cost ($m)*
2411	16.73	332.23	348.96
4000	16.73	332.23	348.96
6000	16.73	332.23	348.96
8000	17.86	331.84	349.70
10000	23.18	330.37	353.55
11828	55.99	324.75	380.73

The effects of a critical parameter, retrofit cost expressed in terms of percentage of new construction costs $\hat{\rho}_s$, were further evaluated on the strategy for both the M_W 5.5 and M_W 7.0 events by using the “low” and “high” ranges from Table 3.2. The optimization model was rerun for these two ranges and the results are reported in Table 4.4 and Table 4.5. For comparisons, the evaluated total costs of the solution (P) were also reported. As illustrated in the table, for the “low” retrofit cost range, as it lowers the weight on the retrofit cost in the objective, selecting enhanced (higher numbered) strategies can help reduce the expected damage cost and the total cost. The “high” retrofit cost range on the other hand makes it more economical to choose strategies that merely meet the capacity.

Table 4.4 Retrofit Strategies and Costs for “Low” and “High” Retrofit Cost Range for M_W 5.5 Event

Desired Throughput (Veh/Hr)	*Retrofit cost ($m)*	*Expected damage cost ($m)*	*Total Cost ($m)*	*Evaluated total cost of solution (P) ($m)*
“Low” Retrofit Cost Range				
14377	5.63	117.02	122.65	136.33
15000	5.63	117.02	122.65	136.33
16500	5.63	117.02	122.65	136.33
18000	5.63	117.02	122.65	136.22
19500	5.63	117.02	122.65	138.49
20841	19.35	116.53	135.88	148.33
“High” Retrofit Cost Range				
14377	0.00	141.74	141.74	150.09
15000	0.15	141.68	141.82	150.09
16500	1.33	141.12	142.45	150.09
18000	3.69	140.56	144.25	159.31
19500	10.36	139.27	149.63	168.09
20841	28.60	136.81	165.41	187.14

Table 4.5 Retrofit Strategies and Costs for "Low" and "High" Retrofit Cost Range for M_W 7.0 Event

Desired Throughput (Veh/Hr)	*Retrofit cost ($m)*	*Expected damage cost ($m)*	*Total Cost ($m)*	*Evaluated total cost of solution (P) ($m)*
"Low" Retrofit Cost Range				
2411	12.41	295.32	307.73	339.25
4000	12.41	295.32	307.73	339.25
6000	12.41	295.32	307.73	339.25
8000	12.41	295.32	307.73	338.85
10000	13.50	295.27	308.76	339.68
11828	43.50	293.81	337.31	363.50
"High" Retrofit Cost Range				
2411	0.00	369.15	369.15	403.47
4000	0.15	369.22	369.37	403.47
6000	4.77	366.07	370.84	403.47
8000	9.29	365.26	374.55	410.44
10000	34.02	354.88	388.90	429.83
11828	75.63	348.18	423.81	495.54

From the results, it is easy to see the benefits of evaluating the current conditions of infrastructure and preparing for future events. As mentioned earlier, the expected damage cost when no retrofitting is applied for the M_W 5.5 event is $142 million with a corresponding traffic capacity of 14,377 veh/hr, and for the M_W 7.0 event the expected damage cost is approximately $369 million with a corresponding traffic capacity of 2,411 veh/hr. From the model results from all cost ranges for the M_W 5.5 event, an overall cost difference (in terms of total system cost) when compared to if no retrofitting was done found (system cost with retrofitting – system cost without retrofitting) to range from $24 million in extra costs to $19 million in savings and was able to raise the traffic throughput by up to 6464 veh/hr (See Figure 4.3). Similarly for the M_W 7.0 event, an overall cost difference ranging from \$55 million in extra costs to \$62 million in savings and the ability to raise the traffic throughput up to 9417 veh/hr was also determined (See Figure 4.4). In some cases the total system cost exceeded the system cost when compared to if no retrofitting was done, it must be seen that the additional cost allows for the traffic throughput of the system to be maintained after an event. Although the total system cost may be lower prior to any retrofitting, the system does not meet the desired traffic capacity set by the model. So even though the baseline damage is used to illustrate the benefits of the model it should not be considered a feasible solution to the model.

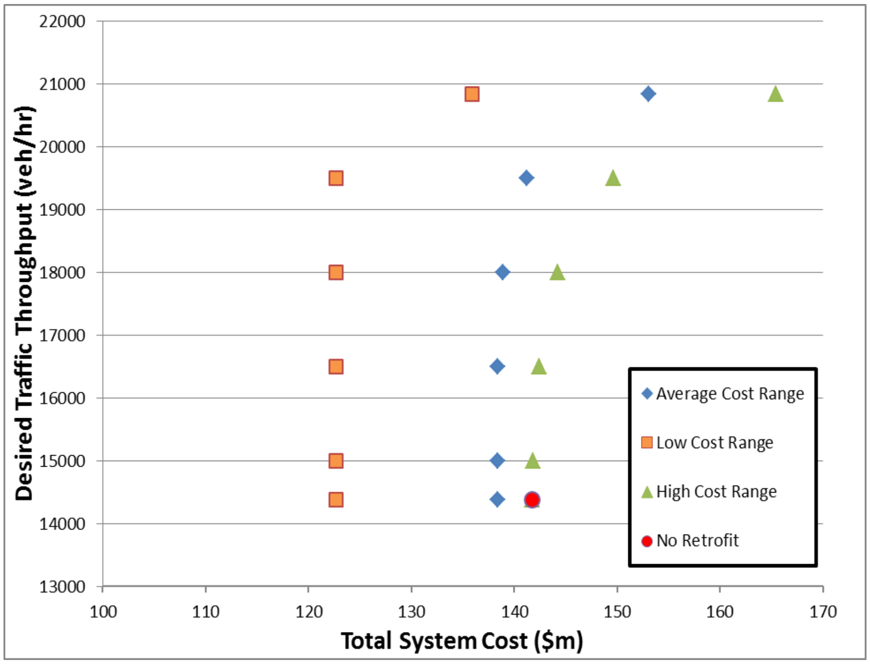


Figure 4.3 Mw 5.5 Solution Comparison

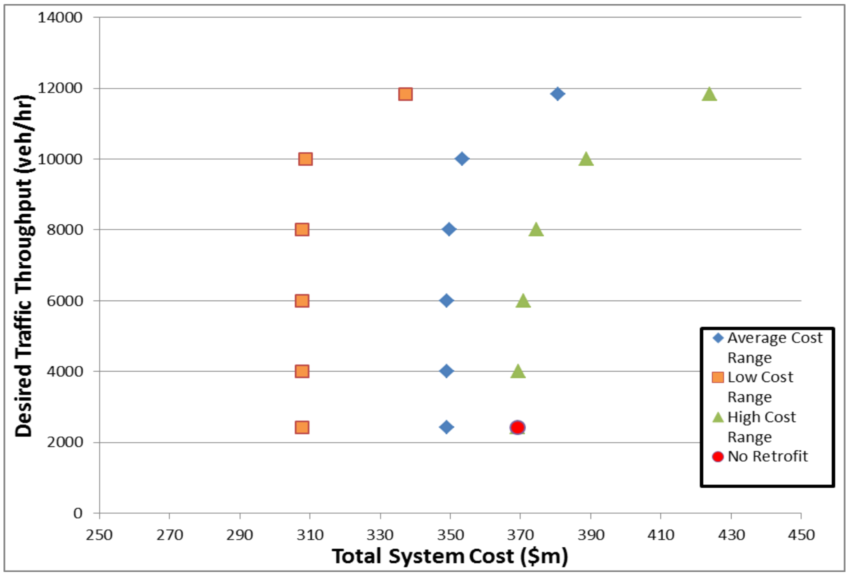


Figure 4.4 Mw 7.0 Solution Comparison

CHAPTER FIVE

SUMMARY AND CONCLUSION

This thesis has introduced a new retrofit strategy decision scheme for highway bridges under seismic hazards and seamlessly integrates the scenario-based seismic analysis of bridges and the traffic network into the proposed optimization modeling framework. The developed model uses this decision scheme to select critical bridges for retrofitting to accommodate a desire throughput while minimizing the total system cost.

5.1 Summary

In this research, an optimal modeling framework to determine best retrofit strategies for a network of highway bridges was developed and applied to the Charleston area. It aims to achieve the least total cost of retrofitting and the subsequent damage while satisfying the traffic capacity of the network. The model explicitly integrates the effects of the traffic network and the bridge seismic assessment of damage states into the retrofit strategy decision scheme.

A simplified four-bridge network and the 1886 Charleston earthquake as the earthquake scenario were used to validate the model, and it was then modified and applied to the Charleston area to demonstrate its applicability. The results indicate that the decisions on the selected retrofit strategy are highly dependent on traffic capacity requirement and related to the network topology. They also justify the importance of integrating the traffic network into the decision making process, and including both the retrofit and sequent damage costs in the objective.

Though the model is developed to cope with seismic hazards, the modeling framework can be generalizable for retrofit strategy design under other kinds of natural disasters, e.g., floods, with appropriate strategies and damage estimates. There are several modeling extensions that can make the decision scheme for more practical considerations, such as integrations of the effects of traffic equilibrium and integrated analysis of bridge structural enhancement strategies.

5.2 Conclusion

In this research it was seen that the choosing of retrofit strategies varies greatly depending on the required network traffic throughput and the costs associated with retrofitting. For a given retrofit price range (low, average, or high), as the desired traffic throughput increases a higher or more enhanced retrofitting strategy is chosen. Furthermore, only the bridges most critical to the traffic capacity of the network received the more enhanced strategies. This was caused by the model choosing to meet the traffic throughput requirement but also choose the lowest system cost outcome. It is interesting to note that for the "high" retrofit cost range many solutions to the model had a higher system cost than if no retrofitting was to be completed. Although the cost may be higher, the model solution allows for the traffic throughput to be met while doing nothing does not.

For the "low" retrofit cost range, a lower weight is placed on the retrofit cost in the objective. This causes the model to select enhanced (or higher numbered) strategies reducing the expected damage cost and the system cost while, in most cases, surpassing the desired traffic throughput of the network. This occurs due to the retrofit benefits to the expected damage outweighing the cost of retrofitting. Adversely, for the “high” retrofit cost range puts a greater weight on the retrofit cost in the objective. This causes the model to choose strategies that merely meet the traffic throughput requirement of the network. This is due to the cost of retrofitting outweighing the reduction to the expected damage of the network. For the “average” retrofit cost range, a balance was seen between the retrofit strategies chosen and meeting capacity. The model would choose to retrofit a majority of bridges with at least strategy S1 (Superstructure), and then only enhance the strategy on the most critical bridges to traffic. This allowed for the network to meet the desired traffic throughput and mitigate expected damages on a majority of bridges.

5.3 Future Work

While this thesis has demonstrated the potential for using modeling to determine retrofitting strategies at minimum costs, many opportunities for extending the scope of this thesis remain. Future research can be accomplished to further this study through the incorporation of a greater number of direct damages, or costs, into the objective, the incorporation of all possible hazards (earthquake, wind, and flood) to a region, and research into true retrofit costs.

The additional direct cost that could be evaluated is the “user” cost. The user cost, in this situation, would be the cost related to the travel delay experienced by the failure or reduced capacity of a bridge within the network. As well the manpower required to redirect traffic from crossing the damaged bridges. The inclusion of the user cost would allow the model to more realistically report the total costs of the system.

The HAZUS program not only models the effects of earthquakes, but also the potential effects of flooding and winds on the desired area. In this thesis, only the potential effects of earthquakes were considered and retrofitted against. To provide a truly effective retrofitting program for the study area, the effects of all hazards should be considered. With all other hazards considered, it would allow for the bridges in the region to have a greater chance of reduced damage if any hazard were to occur and not protected solely from one.

Additionally, there are retrofits that could not only mitigate damage from seismic hazards but from others as well. An example of this is the use of seismic restrainers. Restrainers can not only reduce the chances of the bridge superstructure from falling off its supports, it can prevent the superstructure from lifting off during flooding. This allows for both hazards to be considered within one retrofitting strategy.

As reported in Chapter 4, the retrofitting solutions vary greatly with the cost range associated with each retrofit type. For this research values were adopted from a study done by CALTRANS in California. However, these values varied greatly and the use of the low value versus the high value produced very different results in terms of system costs. Further research into this area will allow for a smaller range to be developed, and greatly reduce the variability in the solutions generated by the model.

REFERENCES

1. Buckle, I. G. *Seismic Retrofitting Manual for Highway Structures*. McLean, VA: Federal Highway Administration, Office of Research, Development and Technology, Turner-Fairbank Highway Research Center, 2006.

2. ASCE. *ASCE | 2013 Report Card for America's Infrastructure*. American Society of Civil Engineers, 2013. Infrastructurereportcard.org. Accessed May 16, 2013.

3. Yin, Y., Madanat, S.M., Lu, X.-Y. Robust improvement schemes for road networks under demand uncertainty. *European Journal of Operational Research*, Vol. 198, No. 2, 2009, pp. 470-479.

4. Basoz, N.I., Kiremidjian, A.S., King, S.A., Law, K.H. Statistical Analysis of Bridge Damage Data from the 1994 Northridge, CA, Earthquake. *Earthquake Spectra*, Vol. 15, No. 1, 1999, pp. 25-54.

5. Liang, Shuh and Wann-Ming Wey. Resource Allocation and Uncertainty in Transportation Infrastructure Planning: A Study of Highway Improvement Program in Taiwan. *Habitat International*, Vol. 39, 2013, pp. 128-36.

6. Werner, S. D., Taylor, C. E., Moore, J. E., and Walton, J. S. *Seismic Retrofitting Manuals for Highway Systems, Volume I, Seismic Risk Analysis of Highway Systems, and Technical Report for Volume I*. Multidisciplinary Center for Earthquake Engineering Research, Buffalo, N.Y, 1999.

7. Nojima, N. *Prioritization in Upgrading Seismic Performance of Road Network Based on System Reliability Analysis*. The 3rd China-Japan-US Trilateral Symposium on Lifeline Earthquake Engineering, 1998.

8. Federal Emergency Management Agency. *HAZUS,* December 2012. http://www.fema.gov/hazus/. Accessed April 12, 2013.

9. FHWA. Seismic Retrofitting Manual for Highway Bridges. Publication FHWA-RD-94 052. FHWA, U.S. Department of Transportation, 1995.

10. McLean, David I., Thad D. Saunders, and Harold H. Hahnenkratt. Seismic Evaluation and Retrofit of Bridge Substructures with Spread and Pile-Supported Foundations. Report Number WA-RD 382.1. Olympia: Washington State Department of Transportation, 1995.

11. Chai, Y.H., Priestley, M.J.N., and Seible, F. Retrofit of Bridge Columns for Enhanced Seismic Performance. Seismic Assessment and Retrofit of Bridges, Report Number SSRP-91/03, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego, 1992.

12. Caltrans. Earthquake Retrofit Guidelines for Bridges. Memo to Designers 20-4, California Department of Transportation, Sacramento, California, 1996.

13. Buckle, I.G. The Northridge, California Earthquake of January 17, 1994: Performance of Highway Bridges. Technical Report NCEER-94-0008, National Center for Earthquake Engineering Research, University at Buffalo, 1994.

14. Shahrikhi, F., and Matula, D. W. On solving large maximum concurrent flow problems. In Proceedings of the ACM Computer Conference. ACM, New York, 1987, 205-209.

15. Attar, R. *A Distributive Adaptive Multi-path Routing-Consistent Making*, 1981, Aiken Computation Laboratory, Harvard University, Cambridge, Mass.

16. Boorstyn, R. R., and Frank, H. Large-scale network topological optimization. *IEEE Communications*, 1977, pp. 29-47.

17. Gerla, M. A cut saturation algorithm for topological design of packet-switched communicationnetworks. In Proceedings of the National Telecommunication Conference. Dec. 1974, pp.1074-1085.

18. Matula, D.W. Divisive vs agglomerative average linkage hierarchical clustering. In *Classification as a Tool of Research*. Gaul, W., and Schader, M., eds. North-Holland, Amsterdam, 1986, pp. 289-301.

19. Biswas, J., and Matula, D. W. *Two-flow routing algorithms for the maximum concurrent flow problem*. In Proceedings of the ACM Fall Joint Conference. ACM, New York, 1986, pp. 629-635.

20. Thompson, B., and Matula, D. W. *A flow rerouting algorithm for the maximum concurrent flow problem with variable capacities and demands, and its applications to cluster analysis*. Tech. Rep. 86-CSE-12. Dept. of Computer Science and Engineering. Southern Methodist Univ., 1986.

21. Kennington, J. L., and Helgason, R. V. *Algorithms for Network Programming*. Wiley, NewYork, 1980.

22. Fan, Y., Liu, C., Lee, R., Kiremidjian, A.S. Highway Network Retrofit Under Seismic Hazard. *Journal of Infrastructure Systems*, Vol. 16, No. 3, 2010, pp. 181-187.

23. Fan, Y., Liu, C. Solving Stochastic Transportation Network Protection Problems Using the Progressive Hedging-based Method. *Networks and Spatial Economics*, Vol. 10, No. 2, 2010, pp. 193-208.

24. Liu, C., Fan, Y., Ordóñez, F. A Two-Stage Stochastic Programming Model for Transportation Network Protection. *Computers & Operations Research*, Vol. 36, No. 5, 2009, pp. 1582-1590.

25. Yang, H., Bell, M.G. Models and Algorithms for Road Network Design: A Review and Some New Developments. *Transport Reviews*, Vol. 18, No. 3, 1998, pp. 257-278.

26. Chang, L., Peng, F., Ouyang, Y., Elnashai, A., Spencer, B. Bridge Seismic Retrofit Program Planning to Maximize Postearthquake Transportation Network Capacity. *Journal of Infrastructure Systems*, Vol. 18, No. 2, 2012, pp. 75-88.

27. BCD Council of Governments. "Long Range Transportation Plan." *Long Range Transportation Plan*. 2010. Web. 13 June 2012. <http://www.bcdcog.com/LRP.htm>.

28. FHWA. "National Bridge Inventory (NBI)." *National Bridge Inventory*. 2011.Web. 06 June 2012. <http://www.fhwa.dot.gov/bridge/nbi.htm>.

29. USDOT. Federal Highway Administration. *Bridge Preservation Guide*. FWHA, 2011. Print.

30. World Media Group. "Charleston, SC Natural Disasters and Weather Extremes." 2010. Web. 12 June 2012. <Charleston, SC Natural Disasters and Weather Extremes>.

31. Cote, Richard N. "SCEARTHQUAKES.COM." *SCEARTHQUAKES.COM*. 2012. Web. 12 June 2012. <http://www.scearthquakes.com/>.

32. Wong, Ivan, Jawhar Bouabid, William Graf, Charles Huyck, Allan Porush, Walter Silva, Timothy Siegel, Gilles Bureau, Ronald Eguchi, and John Knight. *Potential Losses in a Repeat of the 1886 Charleston, South Carolina, Earthquake*. SCEMD, 2005. Web. <http://www.pacificengineering.org/potential/SC%20EQ%20Loss%20Assmt%20HAZUS%20Pubcopy.pdf>.

33. Padgett, Jamie E. , DesRoches, Reginald and Nilsson, Emily 'Regional Seismic Risk Assessment of Bridge Network in Charleston, South Carolina', Journal of Earthquake Engineering, 14: 6, pp. 918- 933, 2010.

34. Kiremidjian, A., Moore, J., Fan, Y. Y., Yazlali, O., Basoz, N., and Williams, M. [2007] ‘‘Seismic risk assessment of transportation networks,’’ Journal of Earthquake Engineering 11, 371–382.

35. Shinozuka, M., Chang, S., Eguchi, R., Abrams, D., Hwang, H., and Rose, A. [1997] ‘‘Advanced in earthquake loss estimation and application to Memphis, TN,’’ Earthquake Spectra 13(4), 739–758

36. Luna, R., Hoffman, D., and Lawrence, W. T. [2008] ‘‘Estimation of earthquake loss due to bridge damage in the St. Louis metropolitan area. I: Direct losses,’’ Natural Hazards Review 9(1), 1–11.

37. Werner, S. D., Taylor, C. E., Moore, III, J. E., Walton, J. S., and Cho, S. [2000] ‘‘A risk-based methodology for assessing the seismic performanceof highway systems,’’ Technical Report No. MCEER-00-0014, Multidisciplinary Center for Earthquake Engineering Research, State University at Buffalo, Buffalo, New York.

38. Kircher, C., Whitman, R., and Holmes, W. [2006] ‘‘HAZUS earthquake loss methodologies,’’ Natural Hazards Review 7(2), 45–60.

39. Werner, S. D., Taylor, C. E., and Moore, J. E. [1997] ‘‘Loss estimation due to seismic risks to highway systems,’’ Earthquake Spectra 13(4), 585–604.

40. GIS/Mapping. South Carolina Department of Transportation, 2008. http://dbw.scdot.org/GISMapping/. Accessed August 31, 2012.

41. J.-U. Klügel, L. Mualchin, G.F. Panza. A Scenario-Based Procedure for Seismic Risk Analysis. Engineering Geology, Volume 88, Issues 1–2, 2006, pp. 1-22.

42. Historic Earthquakes. United States Geological Survey, Nov. 2012. http://earthquake.usgs.gov/earthquakes/states/historical_state.php. Accessed May 5, 2013.

43. Fourer, R., Gay, D., Kernighan, B. AMPL: A Modeling Language for Mathematical Programming, 2nd Ed. Duxbury Press, Boston, 2003.

44. Federal Highway Administration. "Appendix N: Procedures for Estimating Highway Capacity " *Highway Performance Monitoring System: Field Manual*. Office of Highway Policy Information, Sept. 2010.

APPENDICES

Appendix A:

M_W 5.5 Model Probability Data

M_W 5.5 Event						
Do-Nothing (S0)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.104	0.075	0.129	0.285	0.406
	2	0.103	0.134	0.146	0.287	0.33
	3	0.099	0.135	0.145	0.287	0.334
	4	0.099	0.135	0.145	0.287	0.334
	5	0.096	0.132	0.144	0.287	0.341
	6	0.095	0.071	0.125	0.283	0.427
H	7	0.798	0	0.081	0.075	0.046
	8	0.798	0	0.081	0.075	0.046
	9	0.097	0.055	0.119	0.28	0.448
	10	0.102	0.137	0.147	0.286	0.328
	11	0.104	0.122	0.143	0.287	0.344
M	12	0.165	0.175	0.162	0.269	0.229
G	13	0.441	0.296	0.141	0.092	0.029
	14	0.1	0.136	0.146	0.287	0.332
	15	0.1	0.136	0.146	0.287	0.332
	16	0.101	0.136	0.146	0.286	0.33
	17	0.101	0.136	0.146	0.286	0.33
	18	0.713	0	0	0.172	0.115
	19	0.713	0	0	0.172	0.115
	20	0.714	0	0	0.172	0.114
	21	0.722	0	0	0.168	0.11
	22	0.112	0.144	0.15	0.285	0.309
	23	0.112	0.144	0.15	0.285	0.309
	24	0.132	0.157	0.156	0.28	0.275
	25	0.132	0.157	0.156	0.28	0.275
	26	0.14	0.162	0.158	0.277	0.262
	27	0.14	0.162	0.158	0.277	0.262
C	28	0.254	0.185	0.166	0.237	0.158
	29	0.254	0.185	0.166	0.237	0.158
L	30	0.222	0.061	0.155	0.281	0.28
	31	0.879	0.059	0.029	0.025	0.008
	32	0.879	0.059	0.029	0.025	0.008
	33	0.721	0.176	0.048	0.038	0.017
	34	0.721	0.176	0.048	0.038	0.017
	35	0.233	0.2	0.166	0.239	0.162
	36	0.097	0.133	0.144	0.287	0.339
	37	0.793	0	0.082	0.077	0.048
	38	0.737	0.099	0.064	0.069	0.031
	39	0.568	0.234	0.08	0.091	0.028
	40	0.575	0.232	0.078	0.072	0.043
	41	0.578	0.231	0.078	0.071	0.043
	42	0.584	0.229	0.077	0.07	0.041

K	43	0.108	0.141	0.149	0.286	0.316
	44	0.108	0.141	0.149	0.286	0.316
	45	0.198	0.189	0.165	0.255	0.193
	46	0.198	0.189	0.165	0.255	0.193
	47	0.697	0.206	0.063	0.028	0.005
	48	0.697	0.206	0.063	0.028	0.005
	49	0.701	0.204	0.062	0.028	0.005
	50	0.705	0.202	0.061	0.027	0.005
	51	0.718	0.195	0.058	0.025	0.005
	52	0.318	0.217	0.159	0.2	0.107
	53	0.752	0.176	0.049	0.02	0.003
	54	0.775	0.163	0.043	0.017	0.003
	55	0.775	0.163	0.043	0.017	0.003
	56	0.344	0.219	0.155	0.187	0.094
	57	0.344	0.219	0.155	0.187	0.094
	58	0.784	0.158	0.04	0.015	0.002
	59	0.784	0.158	0.04	0.015	0.002
P	60	0.802	0.133	0.045	0.018	0.003
	61	0.802	0.133	0.045	0.018	0.003
	62	0.36	0.22	0.153	0.18	0.087
	63	0.243	0.064	0.159	0.276	0.257
	64	0.243	0.203	0.165	0.234	0.154
	65	0.488	0.146	0.183	0.09	0.093
	66	0.488	0.146	0.183	0.09	0.093
E	67	0.104	0.039	0.116	0.277	0.464
	68	0.104	0.139	0.147	0.286	0.324
	69	0.094	0.131	0.143	0.287	0.344
J	70	0.096	0.132	0.144	0.287	0.341
	71	0.096	0.132	0.144	0.287	0.341
	72	0.097	0.055	0.119	0.279	0.45
	73	0.747	0.103	0.06	0.063	0.027
	74	0.747	0.103	0.06	0.063	0.027
O	75	0.115	0.146	0.151	0.284	0.303
	76	0.827	0	0	0.116	0.057
N	77	0.103	0.138	0.147	0.286	0.326
	78	0.105	0.135	0.147	0.286	0.327
	79	0.105	0.139	0.148	0.286	0.322

M_W 5.5 Event						
Superstructure(S1)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.194	0.068	0.116	0.257	0.365
	2	0.193	0.121	0.131	0.258	0.297
	3	0.189	0.122	0.131	0.258	0.301
	4	0.189	0.122	0.131	0.258	0.301
	5	0.186	0.119	0.130	0.258	0.307
	6	0.185	0.064	0.113	0.255	0.384
H	7	0.818	0.000	0.073	0.068	0.041
	8	0.818	0.000	0.073	0.068	0.041
	9	0.188	0.050	0.107	0.252	0.403
	10	0.192	0.123	0.132	0.257	0.295
	11	0.194	0.110	0.129	0.258	0.310
M	12	0.248	0.158	0.146	0.242	0.206
G	13	0.498	0.266	0.127	0.083	0.026
	14	0.189	0.122	0.131	0.258	0.299
	15	0.189	0.122	0.131	0.258	0.299
	16	0.192	0.122	0.131	0.257	0.297
	17	0.192	0.122	0.131	0.257	0.297
	18	0.742	0.000	0.000	0.155	0.104
	19	0.742	0.000	0.000	0.155	0.104
	20	0.743	0.000	0.000	0.155	0.103
	21	0.750	0.000	0.000	0.151	0.099
	22	0.201	0.130	0.135	0.257	0.278
	23	0.201	0.130	0.135	0.257	0.278
	24	0.219	0.141	0.140	0.252	0.248
	25	0.219	0.141	0.140	0.252	0.248
	26	0.227	0.146	0.142	0.249	0.236
	27	0.227	0.146	0.142	0.249	0.236
C	28	0.329	0.167	0.149	0.213	0.142
	29	0.329	0.167	0.149	0.213	0.142
L	30	0.301	0.055	0.140	0.253	0.252
	31	0.891	0.053	0.026	0.023	0.007
	32	0.891	0.053	0.026	0.023	0.007
	33	0.749	0.158	0.043	0.034	0.015
	34	0.749	0.158	0.043	0.034	0.015
	35	0.310	0.180	0.149	0.215	0.146
	36	0.187	0.120	0.130	0.258	0.305
	37	0.814	0.000	0.074	0.069	0.043
	38	0.763	0.089	0.058	0.062	0.028
	39	0.610	0.211	0.072	0.082	0.025
	40	0.617	0.209	0.070	0.065	0.039
	41	0.619	0.208	0.070	0.064	0.039
	42	0.625	0.206	0.069	0.063	0.037

K	43	0.197	0.127	0.134	0.257	0.284
	44	0.197	0.127	0.134	0.257	0.284
	45	0.278	0.170	0.149	0.230	0.174
	46	0.278	0.170	0.149	0.230	0.174
	47	0.728	0.185	0.057	0.025	0.005
	48	0.728	0.185	0.057	0.025	0.005
	49	0.731	0.184	0.056	0.025	0.005
	50	0.734	0.182	0.055	0.024	0.005
	51	0.745	0.176	0.052	0.023	0.005
	52	0.385	0.195	0.143	0.180	0.096
	53	0.777	0.158	0.044	0.018	0.003
	54	0.797	0.147	0.039	0.015	0.003
	55	0.797	0.147	0.039	0.015	0.003
	56	0.410	0.197	0.140	0.168	0.085
	57	0.410	0.197	0.140	0.168	0.085
	58	0.806	0.142	0.036	0.014	0.002
	59	0.806	0.142	0.036	0.014	0.002
P	60	0.821	0.120	0.041	0.016	0.003
	61	0.821	0.120	0.041	0.016	0.003
	62	0.424	0.198	0.138	0.162	0.078
	63	0.320	0.058	0.143	0.248	0.231
	64	0.320	0.183	0.149	0.211	0.139
	65	0.539	0.131	0.165	0.081	0.084
	66	0.539	0.131	0.165	0.081	0.084
E	67	0.194	0.035	0.104	0.249	0.418
	68	0.194	0.125	0.132	0.257	0.292
	69	0.185	0.118	0.129	0.258	0.310
J	70	0.186	0.119	0.130	0.258	0.307
	71	0.186	0.119	0.130	0.258	0.307
	72	0.187	0.050	0.107	0.251	0.405
	73	0.772	0.093	0.054	0.057	0.024
	74	0.772	0.093	0.054	0.057	0.024
O	75	0.204	0.131	0.136	0.256	0.273
	76	0.844	0.000	0.000	0.104	0.051
N	77	0.193	0.124	0.132	0.257	0.293
	78	0.194	0.122	0.132	0.257	0.294
	79	0.194	0.125	0.133	0.257	0.290

M_W 5.5 Event						
Superstructure & Substructure (S2)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.239	0.064	0.110	0.242	0.345
	2	0.238	0.114	0.124	0.244	0.281
	3	0.234	0.115	0.123	0.244	0.284
	4	0.234	0.115	0.123	0.244	0.284
	5	0.232	0.112	0.122	0.244	0.290
	6	0.230	0.060	0.106	0.241	0.363
H	7	0.828	0.000	0.069	0.064	0.039
	8	0.828	0.000	0.069	0.064	0.039
	9	0.233	0.047	0.101	0.238	0.381
	10	0.237	0.116	0.125	0.243	0.279
	11	0.238	0.104	0.122	0.244	0.292
M	12	0.290	0.149	0.138	0.229	0.195
G	13	0.526	0.252	0.120	0.078	0.025
	14	0.234	0.116	0.124	0.244	0.282
	15	0.234	0.116	0.124	0.244	0.282
	16	0.237	0.116	0.124	0.243	0.281
	17	0.237	0.116	0.124	0.243	0.281
	18	0.756	0.000	0.000	0.146	0.098
	19	0.756	0.000	0.000	0.146	0.098
	20	0.757	0.000	0.000	0.146	0.097
	21	0.764	0.000	0.000	0.143	0.094
	22	0.245	0.122	0.128	0.242	0.263
	23	0.245	0.122	0.128	0.242	0.263
	24	0.262	0.133	0.133	0.238	0.234
	25	0.262	0.133	0.133	0.238	0.234
	26	0.270	0.138	0.134	0.235	0.223
	27	0.270	0.138	0.134	0.235	0.223
C	28	0.366	0.157	0.141	0.201	0.134
	29	0.366	0.157	0.141	0.201	0.134
L	30	0.340	0.052	0.132	0.239	0.238
	31	0.897	0.050	0.025	0.021	0.007
	32	0.897	0.050	0.025	0.021	0.007
	33	0.763	0.150	0.041	0.032	0.014
	34	0.763	0.150	0.041	0.032	0.014
	35	0.348	0.170	0.141	0.203	0.138
	36	0.232	0.113	0.122	0.244	0.288
	37	0.824	0.000	0.070	0.065	0.041
	38	0.776	0.084	0.054	0.059	0.026
	39	0.632	0.199	0.068	0.077	0.024
	40	0.639	0.197	0.066	0.061	0.037
	41	0.640	0.196	0.066	0.060	0.037
	42	0.646	0.195	0.065	0.060	0.035

K	43	0.242	0.120	0.127	0.243	0.269
	44	0.242	0.120	0.127	0.243	0.269
	45	0.318	0.161	0.140	0.217	0.164
	46	0.318	0.161	0.140	0.217	0.164
	47	0.743	0.175	0.054	0.024	0.004
	48	0.743	0.175	0.054	0.024	0.004
	49	0.746	0.173	0.053	0.024	0.004
	50	0.749	0.172	0.052	0.023	0.004
	51	0.759	0.166	0.049	0.021	0.004
	52	0.419	0.184	0.135	0.170	0.091
	53	0.789	0.150	0.042	0.017	0.003
	54	0.808	0.139	0.037	0.014	0.003
	55	0.808	0.139	0.037	0.014	0.003
	56	0.443	0.186	0.132	0.159	0.080
	57	0.443	0.186	0.132	0.159	0.080
	58	0.817	0.134	0.034	0.013	0.002
	59	0.817	0.134	0.034	0.013	0.002
P	60	0.831	0.113	0.038	0.015	0.003
	61	0.831	0.113	0.038	0.015	0.003
	62	0.456	0.187	0.130	0.153	0.074
	63	0.357	0.054	0.135	0.235	0.218
	64	0.357	0.173	0.140	0.199	0.131
	65	0.565	0.124	0.156	0.077	0.079
	66	0.565	0.124	0.156	0.077	0.079
E	67	0.238	0.033	0.099	0.235	0.394
	68	0.238	0.118	0.125	0.243	0.275
	69	0.231	0.111	0.122	0.244	0.292
J	70	0.232	0.112	0.122	0.244	0.290
	71	0.232	0.112	0.122	0.244	0.290
	72	0.232	0.047	0.101	0.237	0.383
	73	0.785	0.088	0.051	0.054	0.023
	74	0.785	0.088	0.051	0.054	0.023
O	75	0.249	0.124	0.128	0.241	0.258
	76	0.853	0.000	0.000	0.099	0.048
N	77	0.238	0.117	0.125	0.243	0.277
	78	0.239	0.115	0.125	0.243	0.278
	79	0.239	0.118	0.126	0.243	0.274

M_W 5.5 Event

Superstructure, Substructure, & Foundation (S3)

Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.284	0.060	0.103	0.228	0.325
	2	0.282	0.107	0.117	0.230	0.264
	3	0.279	0.108	0.116	0.230	0.267
	4	0.279	0.108	0.116	0.230	0.267
	5	0.277	0.106	0.115	0.230	0.273
	6	0.275	0.057	0.100	0.226	0.342
H	7	0.838	0.000	0.065	0.060	0.037
	8	0.838	0.000	0.065	0.060	0.037
	9	0.278	0.044	0.095	0.224	0.358
	10	0.282	0.110	0.118	0.229	0.262
	11	0.283	0.098	0.114	0.230	0.275
M	12	0.332	0.140	0.130	0.215	0.183
G	13	0.554	0.237	0.113	0.074	0.023
	14	0.279	0.109	0.117	0.230	0.266
	15	0.279	0.109	0.117	0.230	0.266
	16	0.282	0.109	0.117	0.229	0.264
	17	0.282	0.109	0.117	0.229	0.264
	18	0.770	0.000	0.000	0.138	0.092
	19	0.770	0.000	0.000	0.138	0.092
	20	0.771	0.000	0.000	0.138	0.091
	21	0.778	0.000	0.000	0.134	0.088
	22	0.290	0.115	0.120	0.228	0.247
	23	0.290	0.115	0.120	0.228	0.247
	24	0.306	0.126	0.125	0.224	0.220
	25	0.306	0.126	0.125	0.224	0.220
	26	0.313	0.130	0.126	0.222	0.210
	27	0.313	0.130	0.126	0.222	0.210
C	28	0.403	0.148	0.133	0.190	0.126
	29	0.403	0.148	0.133	0.190	0.126
L	30	0.378	0.049	0.124	0.225	0.224
	31	0.903	0.047	0.023	0.020	0.006
	32	0.903	0.047	0.023	0.020	0.006
	33	0.777	0.141	0.038	0.030	0.014
	34	0.777	0.141	0.038	0.030	0.014
	35	0.386	0.160	0.133	0.191	0.130
	36	0.278	0.106	0.115	0.230	0.271
	37	0.834	0.000	0.066	0.062	0.038
	38	0.790	0.079	0.051	0.055	0.025
	39	0.654	0.187	0.064	0.073	0.022
	40	0.660	0.186	0.062	0.058	0.034
	41	0.662	0.185	0.062	0.057	0.034
	42	0.666	0.183	0.062	0.056	0.033

K	43	0.286	0.113	0.119	0.229	0.253
	44	0.286	0.113	0.119	0.229	0.253
	45	0.358	0.151	0.132	0.204	0.154
	46	0.358	0.151	0.132	0.204	0.154
	47	0.758	0.165	0.050	0.022	0.004
	48	0.758	0.165	0.050	0.022	0.004
	49	0.761	0.163	0.050	0.022	0.004
	50	0.764	0.162	0.049	0.022	0.004
	51	0.774	0.156	0.046	0.020	0.004
	52	0.454	0.174	0.127	0.160	0.086
	53	0.802	0.141	0.039	0.016	0.002
	54	0.819	0.130	0.034	0.014	0.002
	55	0.819	0.130	0.034	0.014	0.002
	56	0.476	0.175	0.124	0.150	0.075
	57	0.476	0.175	0.124	0.150	0.075
	58	0.828	0.126	0.032	0.012	0.002
	59	0.828	0.126	0.032	0.012	0.002
P	60	0.841	0.106	0.036	0.014	0.002
	61	0.841	0.106	0.036	0.014	0.002
	62	0.488	0.176	0.122	0.144	0.070
	63	0.395	0.051	0.127	0.221	0.206
	64	0.395	0.162	0.132	0.187	0.123
	65	0.590	0.117	0.146	0.072	0.074
	66	0.590	0.117	0.146	0.072	0.074
E	67	0.283	0.031	0.093	0.222	0.371
	68	0.283	0.111	0.118	0.229	0.259
	69	0.276	0.105	0.114	0.230	0.275
J	70	0.277	0.106	0.115	0.230	0.273
	71	0.277	0.106	0.115	0.230	0.273
	72	0.278	0.044	0.095	0.223	0.360
	73	0.798	0.082	0.048	0.050	0.022
	74	0.798	0.082	0.048	0.050	0.022
O	75	0.293	0.117	0.121	0.227	0.242
	76	0.862	0.000	0.000	0.093	0.046
N	77	0.282	0.110	0.118	0.229	0.261
	78	0.284	0.108	0.118	0.229	0.262
	79	0.284	0.111	0.118	0.229	0.258

M_W 5.5 Event						
Complete Replacement (S4)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.329	0.056	0.097	0.214	0.304
	2	0.327	0.100	0.109	0.215	0.247
	3	0.324	0.101	0.109	0.215	0.250
	4	0.324	0.101	0.109	0.215	0.250
	5	0.322	0.099	0.108	0.215	0.256
	6	0.321	0.053	0.094	0.212	0.320
H	7	0.849	0.000	0.061	0.056	0.034
	8	0.849	0.000	0.061	0.056	0.034
	9	0.324	0.041	0.089	0.210	0.336
	10	0.327	0.103	0.110	0.214	0.246
	11	0.328	0.091	0.107	0.215	0.258
M	12	0.374	0.131	0.121	0.202	0.172
G	13	0.582	0.222	0.106	0.069	0.022
	14	0.324	0.102	0.109	0.215	0.249
	15	0.324	0.102	0.109	0.215	0.249
	16	0.327	0.102	0.109	0.214	0.247
	17	0.327	0.102	0.109	0.214	0.247
	18	0.785	0.000	0.000	0.129	0.086
	19	0.785	0.000	0.000	0.129	0.086
	20	0.786	0.000	0.000	0.129	0.085
	21	0.792	0.000	0.000	0.126	0.082
	22	0.334	0.108	0.112	0.214	0.232
	23	0.334	0.108	0.112	0.214	0.232
	24	0.349	0.118	0.117	0.210	0.206
	25	0.349	0.118	0.117	0.210	0.206
	26	0.356	0.121	0.118	0.208	0.196
	27	0.356	0.121	0.118	0.208	0.196
C	28	0.441	0.139	0.124	0.178	0.118
	29	0.441	0.139	0.124	0.178	0.118
L	30	0.417	0.046	0.116	0.211	0.210
	31	0.909	0.044	0.022	0.019	0.006
	32	0.909	0.044	0.022	0.019	0.006
	33	0.791	0.132	0.036	0.028	0.013
	34	0.791	0.132	0.036	0.028	0.013
	35	0.425	0.150	0.124	0.179	0.121
	36	0.323	0.100	0.108	0.215	0.254
	37	0.845	0.000	0.061	0.058	0.036
	38	0.803	0.074	0.048	0.052	0.023
	39	0.675	0.175	0.060	0.068	0.021
	40	0.681	0.174	0.058	0.054	0.032
	41	0.683	0.173	0.058	0.053	0.032
	42	0.687	0.172	0.058	0.052	0.031

K	43	0.331	0.106	0.112	0.214	0.237
	44	0.331	0.106	0.112	0.214	0.237
	45	0.399	0.142	0.124	0.191	0.145
	46	0.399	0.142	0.124	0.191	0.145
	47	0.774	0.154	0.047	0.021	0.004
	48	0.774	0.154	0.047	0.021	0.004
	49	0.776	0.153	0.046	0.021	0.004
	50	0.779	0.151	0.046	0.020	0.004
	51	0.788	0.146	0.043	0.019	0.004
	52	0.488	0.163	0.119	0.150	0.080
	53	0.814	0.132	0.037	0.015	0.002
	54	0.831	0.122	0.032	0.013	0.002
	55	0.831	0.122	0.032	0.013	0.002
	56	0.509	0.164	0.116	0.140	0.070
	57	0.509	0.164	0.116	0.140	0.070
	58	0.839	0.118	0.030	0.011	0.001
	59	0.839	0.118	0.030	0.011	0.001
P	60	0.851	0.100	0.034	0.013	0.002
	61	0.851	0.100	0.034	0.013	0.002
	62	0.520	0.165	0.115	0.135	0.065
	63	0.433	0.048	0.119	0.207	0.193
	64	0.433	0.152	0.124	0.175	0.115
	65	0.616	0.109	0.137	0.067	0.070
	66	0.616	0.109	0.137	0.067	0.070
E	67	0.328	0.029	0.087	0.208	0.348
	68	0.328	0.104	0.110	0.214	0.243
	69	0.321	0.098	0.107	0.215	0.258
J	70	0.322	0.099	0.108	0.215	0.256
	71	0.322	0.099	0.108	0.215	0.256
	72	0.323	0.041	0.089	0.209	0.337
	73	0.810	0.077	0.045	0.047	0.020
	74	0.810	0.077	0.045	0.047	0.020
O	75	0.337	0.109	0.113	0.213	0.227
	76	0.870	0.000	0.000	0.087	0.043
N	77	0.327	0.103	0.110	0.214	0.244
	78	0.329	0.101	0.110	0.214	0.245
	79	0.329	0.104	0.111	0.214	0.241

M_W 7.0 Model Probability Data

M_W 7.0 Event						
Do-Nothing (S0)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.003	0.005	0.016	0.086	0.889
	2	0.003	0.011	0.024	0.114	0.847
	3	0.003	0.011	0.023	0.109	0.854
	4	0.003	0.011	0.023	0.109	0.854
	5	0.003	0.010	0.021	0.103	0.863
	6	0.003	0.004	0.013	0.073	0.907
H	7	0.252	0.000	0.117	0.203	0.427
	8	0.252	0.000	0.117	0.203	0.427
	9	0.003	0.003	0.012	0.068	0.915
	10	0.003	0.011	0.024	0.112	0.850
	11	0.003	0.010	0.022	0.106	0.859
M	12	0.009	0.026	0.047	0.173	0.745
G	13	0.050	0.144	0.175	0.283	0.348
	14	0.003	0.011	0.023	0.110	0.854
	15	0.003	0.011	0.023	0.110	0.854
	16	0.003	0.011	0.024	0.111	0.850
	17	0.003	0.011	0.024	0.111	0.850
	18	0.180	0.000	0.000	0.211	0.610
	19	0.180	0.000	0.000	0.211	0.610
	20	0.176	0.000	0.000	0.209	0.616
	21	0.193	0.000	0.000	0.216	0.591
	22	0.004	0.014	0.029	0.127	0.826
	23	0.004	0.014	0.029	0.127	0.826
	24	0.006	0.018	0.036	0.146	0.794
	25	0.006	0.018	0.036	0.146	0.794
	26	0.006	0.020	0.037	0.151	0.786
	27	0.006	0.020	0.037	0.151	0.786
C	28	0.029	0.054	0.084	0.242	0.592
	29	0.029	0.054	0.084	0.242	0.592
L	30	0.014	0.008	0.034	0.140	0.804
	31	0.396	0.147	0.117	0.180	0.161
	32	0.396	0.147	0.117	0.180	0.161
	33	0.207	0.237	0.133	0.184	0.238
	34	0.207	0.237	0.133	0.184	0.238
	35	0.015	0.038	0.062	0.206	0.678
	36	0.003	0.010	0.022	0.105	0.860
	37	0.242	0.000	0.115	0.203	0.439
	38	0.194	0.108	0.113	0.228	0.357
	39	0.095	0.168	0.119	0.283	0.336
	40	0.101	0.173	0.121	0.204	0.401
	41	0.104	0.176	0.122	0.204	0.395
	42	0.109	0.180	0.123	0.204	0.383

K	43	0.004	0.014	0.028	0.124	0.830
	44	0.004	0.014	0.028	0.124	0.830
	45	0.019	0.047	0.072	0.224	0.637
	46	0.019	0.047	0.072	0.224	0.637
	47	0.256	0.295	0.194	0.172	0.083
	48	0.256	0.295	0.194	0.172	0.083
	49	0.256	0.295	0.194	0.172	0.083
	50	0.258	0.295	0.194	0.171	0.082
	51	0.260	0.296	0.193	0.170	0.081
	52	0.038	0.074	0.100	0.263	0.525
	53	0.267	0.297	0.192	0.166	0.078
	54	0.276	0.299	0.189	0.161	0.074
	55	0.276	0.299	0.189	0.161	0.074
	56	0.040	0.077	0.103	0.266	0.513
	57	0.040	0.077	0.103	0.266	0.513
	58	0.279	0.299	0.188	0.160	0.073
	59	0.279	0.299	0.188	0.160	0.073
P	60	0.289	0.254	0.196	0.176	0.087
	61	0.289	0.254	0.196	0.176	0.087
	62	0.041	0.078	0.104	0.267	0.510
	63	0.027	0.014	0.053	0.187	0.719
	64	0.027	0.059	0.086	0.244	0.584
	65	0.085	0.073	0.171	0.162	0.509
	66	0.085	0.073	0.171	0.162	0.509
E	67	0.003	0.002	0.012	0.067	0.915
	68	0.003	0.012	0.025	0.116	0.843
	69	0.002	0.009	0.020	0.100	0.867
J	70	0.003	0.010	0.021	0.103	0.863
	71	0.003	0.010	0.021	0.103	0.863
	72	0.003	0.003	0.012	0.067	0.916
	73	0.207	0.121	0.116	0.226	0.330
	74	0.207	0.121	0.116	0.226	0.330
O	75	0.004	0.015	0.031	0.132	0.818
	76	0.320	0.000	0.000	0.248	0.433
N	77	0.003	0.011	0.024	0.113	0.848
	78	0.003	0.012	0.025	0.114	0.846
	79	0.003	0.012	0.025	0.116	0.843

M_W 7.0 Event						
Superstructure(S1)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.104	0.005	0.014	0.077	0.800
	2	0.104	0.010	0.022	0.103	0.762
	3	0.103	0.010	0.021	0.098	0.769
	4	0.103	0.010	0.021	0.098	0.769
	5	0.103	0.009	0.019	0.093	0.777
	6	0.103	0.004	0.012	0.066	0.816
H	7	0.328	0.000	0.105	0.183	0.384
	8	0.328	0.000	0.105	0.183	0.384
	9	0.102	0.003	0.011	0.061	0.824
	10	0.103	0.010	0.022	0.101	0.765
	11	0.103	0.009	0.020	0.095	0.773
M	12	0.108	0.023	0.042	0.156	0.671
G	13	0.145	0.130	0.158	0.255	0.313
	14	0.102	0.010	0.021	0.099	0.769
	15	0.102	0.010	0.021	0.099	0.769
	16	0.104	0.010	0.022	0.100	0.765
	17	0.104	0.010	0.022	0.100	0.765
	18	0.261	0.000	0.000	0.190	0.549
	19	0.261	0.000	0.000	0.190	0.549
	20	0.257	0.000	0.000	0.188	0.554
	21	0.274	0.000	0.000	0.194	0.532
	22	0.104	0.013	0.026	0.114	0.743
	23	0.104	0.013	0.026	0.114	0.743
	24	0.105	0.016	0.032	0.131	0.715
	25	0.105	0.016	0.032	0.131	0.715
	26	0.105	0.018	0.033	0.136	0.707
	27	0.105	0.018	0.033	0.136	0.707
C	28	0.125	0.049	0.076	0.218	0.533
	29	0.125	0.049	0.076	0.218	0.533
L	30	0.113	0.007	0.031	0.126	0.724
	31	0.455	0.132	0.105	0.162	0.145
	32	0.455	0.132	0.105	0.162	0.145
	33	0.287	0.213	0.120	0.166	0.214
	34	0.287	0.213	0.120	0.166	0.214
	35	0.114	0.034	0.056	0.185	0.610
	36	0.103	0.009	0.020	0.095	0.774
	37	0.319	0.000	0.104	0.183	0.395
	38	0.275	0.097	0.102	0.205	0.321
	39	0.185	0.151	0.107	0.255	0.302
	40	0.191	0.156	0.109	0.184	0.361
	41	0.193	0.158	0.110	0.184	0.356
	42	0.199	0.162	0.111	0.184	0.345

K	43	0.104	0.013	0.025	0.112	0.747
	44	0.104	0.013	0.025	0.112	0.747
	45	0.118	0.042	0.065	0.202	0.573
	46	0.118	0.042	0.065	0.202	0.573
	47	0.330	0.266	0.175	0.155	0.075
	48	0.330	0.266	0.175	0.155	0.075
	49	0.330	0.266	0.175	0.155	0.075
	50	0.332	0.266	0.175	0.154	0.074
	51	0.334	0.266	0.174	0.153	0.073
	52	0.134	0.067	0.090	0.237	0.473
	53	0.340	0.267	0.173	0.149	0.070
	54	0.349	0.269	0.170	0.145	0.067
	55	0.349	0.269	0.170	0.145	0.067
	56	0.137	0.069	0.093	0.239	0.462
	57	0.137	0.069	0.093	0.239	0.462
	58	0.352	0.269	0.169	0.144	0.066
	59	0.352	0.269	0.169	0.144	0.066
P	60	0.358	0.229	0.176	0.158	0.078
	61	0.358	0.229	0.176	0.158	0.078
	62	0.137	0.070	0.094	0.240	0.459
	63	0.124	0.013	0.048	0.168	0.647
	64	0.124	0.053	0.077	0.220	0.526
	65	0.176	0.066	0.154	0.146	0.458
	66	0.176	0.066	0.154	0.146	0.458
E	67	0.104	0.002	0.011	0.060	0.824
	68	0.104	0.011	0.023	0.104	0.759
	69	0.104	0.008	0.018	0.090	0.780
J	70	0.103	0.009	0.019	0.093	0.777
	71	0.103	0.009	0.019	0.093	0.777
	72	0.102	0.003	0.011	0.060	0.824
	73	0.286	0.109	0.104	0.203	0.297
	74	0.286	0.109	0.104	0.203	0.297
O	75	0.104	0.014	0.028	0.119	0.736
	76	0.387	0.000	0.000	0.223	0.390
N	77	0.104	0.010	0.022	0.102	0.763
	78	0.103	0.011	0.023	0.103	0.761
	79	0.104	0.011	0.023	0.104	0.759

M_W 7.0 Event						
Superstructure & Substructure (S2)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.153	0.004	0.014	0.073	0.756
	2	0.153	0.009	0.020	0.097	0.720
	3	0.153	0.009	0.020	0.093	0.726
	4	0.153	0.009	0.020	0.093	0.726
	5	0.153	0.009	0.018	0.088	0.734
	6	0.153	0.003	0.011	0.062	0.771
H	7	0.365	0.000	0.099	0.173	0.363
	8	0.365	0.000	0.099	0.173	0.363
	9	0.152	0.003	0.010	0.058	0.778
	10	0.153	0.009	0.020	0.095	0.723
	11	0.153	0.009	0.019	0.090	0.730
M	12	0.158	0.022	0.040	0.147	0.633
G	13	0.192	0.122	0.149	0.241	0.296
	14	0.152	0.009	0.020	0.094	0.726
	15	0.152	0.009	0.020	0.094	0.726
	16	0.153	0.009	0.020	0.094	0.723
	17	0.153	0.009	0.020	0.094	0.723
	18	0.302	0.000	0.000	0.179	0.519
	19	0.302	0.000	0.000	0.179	0.519
	20	0.299	0.000	0.000	0.178	0.524
	21	0.314	0.000	0.000	0.184	0.502
	22	0.153	0.012	0.025	0.108	0.702
	23	0.153	0.012	0.025	0.108	0.702
	24	0.155	0.015	0.031	0.124	0.675
	25	0.155	0.015	0.031	0.124	0.675
	26	0.155	0.017	0.031	0.128	0.668
	27	0.155	0.017	0.031	0.128	0.668
C	28	0.174	0.046	0.071	0.206	0.503
	29	0.174	0.046	0.071	0.206	0.503
L	30	0.162	0.007	0.029	0.119	0.683
	31	0.486	0.125	0.099	0.153	0.137
	32	0.486	0.125	0.099	0.153	0.137
	33	0.327	0.201	0.113	0.156	0.202
	34	0.327	0.201	0.113	0.156	0.202
	35	0.164	0.032	0.053	0.175	0.576
	36	0.153	0.009	0.019	0.089	0.731
	37	0.357	0.000	0.098	0.173	0.373
	38	0.315	0.092	0.096	0.194	0.303
	39	0.230	0.143	0.101	0.241	0.286
	40	0.236	0.147	0.103	0.173	0.341
	41	0.238	0.150	0.104	0.173	0.336
	42	0.243	0.153	0.105	0.173	0.326

K	43	0.153	0.012	0.024	0.105	0.706
	44	0.153	0.012	0.024	0.105	0.706
	45	0.167	0.040	0.061	0.190	0.541
	46	0.167	0.040	0.061	0.190	0.541
	47	0.368	0.251	0.165	0.146	0.071
	48	0.368	0.251	0.165	0.146	0.071
	49	0.368	0.251	0.165	0.146	0.071
	50	0.369	0.251	0.165	0.145	0.070
	51	0.371	0.252	0.164	0.145	0.069
	52	0.182	0.063	0.085	0.224	0.446
	53	0.377	0.252	0.163	0.141	0.066
	54	0.385	0.254	0.161	0.137	0.063
	55	0.385	0.254	0.161	0.137	0.063
	56	0.185	0.065	0.088	0.226	0.436
	57	0.185	0.065	0.088	0.226	0.436
	58	0.388	0.254	0.160	0.136	0.062
	59	0.388	0.254	0.160	0.136	0.062
P	60	0.394	0.216	0.167	0.150	0.074
	61	0.394	0.216	0.167	0.150	0.074
	62	0.185	0.066	0.088	0.227	0.434
	63	0.173	0.012	0.045	0.159	0.611
	64	0.173	0.050	0.073	0.207	0.496
	65	0.222	0.062	0.145	0.138	0.433
	66	0.222	0.062	0.145	0.138	0.433
E	67	0.153	0.002	0.010	0.057	0.778
	68	0.153	0.010	0.021	0.099	0.717
	69	0.153	0.008	0.017	0.085	0.737
J	70	0.153	0.009	0.018	0.088	0.734
	71	0.153	0.009	0.018	0.088	0.734
	72	0.152	0.003	0.010	0.057	0.779
	73	0.326	0.103	0.099	0.192	0.281
	74	0.326	0.103	0.099	0.192	0.281
O	75	0.153	0.013	0.026	0.112	0.695
	76	0.421	0.000	0.000	0.211	0.368
N	77	0.153	0.009	0.020	0.096	0.721
	78	0.153	0.010	0.021	0.097	0.719
	79	0.153	0.010	0.021	0.099	0.717

M_W 7.0 Event						
Superstructure, Substructure, & Foundation (S3)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.203	0.004	0.013	0.069	0.711
	2	0.203	0.009	0.019	0.091	0.678
	3	0.202	0.009	0.018	0.087	0.683
	4	0.202	0.009	0.018	0.087	0.683
	5	0.202	0.008	0.017	0.082	0.690
	6	0.202	0.003	0.010	0.058	0.726
H	7	0.402	0.000	0.094	0.162	0.342
	8	0.402	0.000	0.094	0.162	0.342
	9	0.202	0.002	0.010	0.054	0.732
	10	0.202	0.009	0.019	0.090	0.680
	11	0.202	0.008	0.018	0.085	0.687
M	12	0.207	0.021	0.038	0.138	0.596
G	13	0.240	0.115	0.140	0.226	0.278
	14	0.202	0.009	0.018	0.088	0.683
	15	0.202	0.009	0.018	0.088	0.683
	16	0.203	0.009	0.019	0.089	0.680
	17	0.203	0.009	0.019	0.089	0.680
	18	0.343	0.000	0.000	0.169	0.488
	19	0.343	0.000	0.000	0.169	0.488
	20	0.340	0.000	0.000	0.167	0.493
	21	0.354	0.000	0.000	0.173	0.473
	22	0.203	0.011	0.023	0.102	0.661
	23	0.203	0.011	0.023	0.102	0.661
	24	0.205	0.014	0.029	0.117	0.635
	25	0.205	0.014	0.029	0.117	0.635
	26	0.205	0.016	0.030	0.121	0.629
	27	0.205	0.016	0.030	0.121	0.629
C	28	0.222	0.043	0.067	0.194	0.474
	29	0.222	0.043	0.067	0.194	0.474
L	30	0.211	0.006	0.027	0.112	0.643
	31	0.516	0.118	0.094	0.144	0.129
	32	0.516	0.118	0.094	0.144	0.129
	33	0.366	0.190	0.106	0.147	0.190
	34	0.366	0.190	0.106	0.147	0.190
	35	0.213	0.030	0.050	0.165	0.542
	36	0.202	0.008	0.018	0.084	0.688
	37	0.394	0.000	0.092	0.162	0.351
	38	0.355	0.086	0.090	0.182	0.286
	39	0.275	0.134	0.095	0.226	0.269
	40	0.281	0.138	0.097	0.163	0.321
	41	0.282	0.141	0.098	0.163	0.316
	42	0.288	0.144	0.098	0.163	0.306

K	43	0.203	0.011	0.022	0.099	0.664
	44	0.203	0.011	0.022	0.099	0.664
	45	0.216	0.038	0.058	0.179	0.510
	46	0.216	0.038	0.058	0.179	0.510
	47	0.405	0.236	0.155	0.138	0.066
	48	0.405	0.236	0.155	0.138	0.066
	49	0.405	0.236	0.155	0.138	0.066
	50	0.406	0.236	0.155	0.137	0.066
	51	0.408	0.237	0.154	0.136	0.065
	52	0.230	0.059	0.080	0.210	0.420
	53	0.414	0.238	0.154	0.133	0.062
	54	0.422	0.239	0.151	0.129	0.059
	55	0.422	0.239	0.151	0.129	0.059
	56	0.233	0.062	0.082	0.213	0.410
	57	0.233	0.062	0.082	0.213	0.410
	58	0.424	0.239	0.150	0.128	0.058
	59	0.424	0.239	0.150	0.128	0.058
P	60	0.430	0.203	0.157	0.141	0.070
	61	0.430	0.203	0.157	0.141	0.070
	62	0.233	0.062	0.083	0.214	0.408
	63	0.222	0.011	0.042	0.150	0.575
	64	0.222	0.047	0.069	0.195	0.467
	65	0.268	0.058	0.137	0.130	0.407
	66	0.268	0.058	0.137	0.130	0.407
E	67	0.203	0.002	0.010	0.054	0.732
	68	0.203	0.010	0.020	0.093	0.674
	69	0.203	0.007	0.016	0.080	0.694
J	70	0.202	0.008	0.017	0.082	0.690
	71	0.202	0.008	0.017	0.082	0.690
	72	0.202	0.002	0.010	0.054	0.733
	73	0.366	0.097	0.093	0.181	0.264
	74	0.366	0.097	0.093	0.181	0.264
O	75	0.203	0.012	0.025	0.106	0.654
	76	0.455	0.000	0.000	0.198	0.346
N	77	0.203	0.009	0.019	0.090	0.678
	78	0.202	0.010	0.020	0.091	0.677
	79	0.203	0.010	0.020	0.093	0.674

M_W 7.0 Event						
Complete Replacement (S4)						
Bridge Group	Bridge Number	None (d0)	Minor (d1)	Moderate (d2)	Extensive (d3)	Complete (d4)
Q	1	0.253	0.004	0.012	0.064	0.667
	2	0.253	0.008	0.018	0.085	0.635
	3	0.252	0.008	0.017	0.082	0.640
	4	0.252	0.008	0.017	0.082	0.640
	5	0.252	0.007	0.016	0.077	0.647
	6	0.252	0.003	0.010	0.055	0.680
H	7	0.440	0.000	0.088	0.152	0.320
	8	0.440	0.000	0.088	0.152	0.320
	9	0.252	0.002	0.009	0.051	0.686
	10	0.252	0.008	0.018	0.084	0.637
	11	0.252	0.007	0.016	0.079	0.644
M	12	0.257	0.019	0.035	0.130	0.559
G	13	0.288	0.108	0.131	0.212	0.261
	14	0.252	0.008	0.017	0.082	0.640
	15	0.252	0.008	0.017	0.082	0.640
	16	0.253	0.008	0.018	0.083	0.637
	17	0.253	0.008	0.018	0.083	0.637
	18	0.384	0.000	0.000	0.158	0.457
	19	0.384	0.000	0.000	0.158	0.457
	20	0.381	0.000	0.000	0.157	0.462
	21	0.395	0.000	0.000	0.162	0.443
	22	0.253	0.010	0.022	0.095	0.619
	23	0.253	0.010	0.022	0.095	0.619
	24	0.255	0.013	0.027	0.109	0.595
	25	0.255	0.013	0.027	0.109	0.595
	26	0.255	0.015	0.028	0.113	0.589
	27	0.255	0.015	0.028	0.113	0.589
C	28	0.271	0.040	0.063	0.181	0.444
	29	0.271	0.040	0.063	0.181	0.444
L	30	0.261	0.006	0.025	0.105	0.603
	31	0.546	0.110	0.088	0.135	0.121
	32	0.546	0.110	0.088	0.135	0.121
	33	0.406	0.178	0.100	0.138	0.178
	34	0.406	0.178	0.100	0.138	0.178
	35	0.262	0.028	0.046	0.154	0.508
	36	0.252	0.007	0.016	0.079	0.645
	37	0.432	0.000	0.086	0.152	0.329
	38	0.396	0.081	0.085	0.171	0.268
	39	0.321	0.126	0.089	0.212	0.252
	40	0.326	0.130	0.091	0.153	0.301
	41	0.327	0.132	0.091	0.153	0.296
	42	0.333	0.135	0.092	0.153	0.287

K	43	0.253	0.010	0.021	0.093	0.622
	44	0.253	0.010	0.021	0.093	0.622
	45	0.265	0.035	0.054	0.168	0.478
	46	0.265	0.035	0.054	0.168	0.478
	47	0.442	0.221	0.145	0.129	0.062
	48	0.442	0.221	0.145	0.129	0.062
	49	0.442	0.221	0.145	0.129	0.062
	50	0.444	0.221	0.145	0.128	0.061
	51	0.445	0.222	0.145	0.127	0.061
	52	0.279	0.055	0.075	0.197	0.394
	53	0.450	0.223	0.144	0.124	0.058
	54	0.458	0.224	0.142	0.121	0.055
	55	0.458	0.224	0.142	0.121	0.055
	56	0.281	0.058	0.077	0.199	0.385
	57	0.281	0.058	0.077	0.199	0.385
	58	0.460	0.224	0.141	0.120	0.055
	59	0.460	0.224	0.141	0.120	0.055
P	60	0.465	0.190	0.147	0.132	0.065
	61	0.465	0.190	0.147	0.132	0.065
	62	0.281	0.058	0.078	0.200	0.382
	63	0.270	0.010	0.040	0.140	0.539
	64	0.270	0.044	0.064	0.183	0.438
	65	0.314	0.055	0.128	0.121	0.382
	66	0.314	0.055	0.128	0.121	0.382
E	67	0.253	0.001	0.009	0.050	0.686
	68	0.253	0.009	0.019	0.087	0.632
	69	0.253	0.007	0.015	0.075	0.650
J	70	0.252	0.007	0.016	0.077	0.647
	71	0.252	0.007	0.016	0.077	0.647
	72	0.252	0.002	0.009	0.050	0.687
	73	0.405	0.091	0.087	0.169	0.247
	74	0.405	0.091	0.087	0.169	0.247
O	75	0.253	0.011	0.023	0.099	0.613
	76	0.489	0.000	0.000	0.186	0.325
N	77	0.253	0.008	0.018	0.085	0.636
	78	0.252	0.009	0.019	0.085	0.634
	79	0.253	0.009	0.019	0.087	0.632

Appendix B: Procedures for Estimating Highway Capacity (*44*)

HPMS Field Manual

Appendix N: Procedures for Estimating Highway Capacity

Freeway Capacity

Application

All highways (rural and urban) that are "freeway by design" use the following procedures. These are facilities with:

- Four or more through lanes with two-way flow (Data Item 34 >= 4 and Data Item 27 = 2) **OR**two or more through lanes and one-way flow (Data Item 34 >= 2 and Data Item 27 = 1)
- Divided Highways - median width >= 4 feet (Data Item 57) or with a "positive" or "curbed" barrier (Data Item 56 = 1 or 2)
- Access-Controlled Highways (Data Item 55 = 1)

Procedure

Step 1: Calculate Free Flow Speed (FFS)

The first step in the procedure is to estimate free flow speed (FFS) of the facility. *HCM* Equation 23-1 is applied directly:

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} \quad (1)$$

Where:

$BFFS$ = base free flow speed

f_{LW} = adjustment factor for lane width

f_{LC} = adjustment factor for right shoulder lateral clearance

f_N = adjustment factor for number of lanes

f_{ID} = adjustment factor for interchange density

Base Free Flow Speed

BFFS is set at 70 mph for urban facilities and 75 mph for rural facilities.

Adjustment Factor for Lane Width (f_{LW})

The values from *HCM* Exhibit 23-4 are used and are directly based on the values of Data Item 54:

Lane Width	Reduction in FFS (mph; f_{LW})
12 ft.	0.0
11 ft.	1.9
<=10 ft.	6.6

Adjustment Factor for Right Shoulder Lateral Clearance (f_{LC})

The values from *HCM* Exhibit 23-5 (shown as Table 1 here) are used and based directly on the values of Data Item 59. The number of lanes in one direction are computed by halving Data Item 34 for two-way facilities or by using Data

Item 34 directly for one-way facilities:

Table 1. Influence of Right Shoulder Widths on FFS

Right Shoulder Width	Reduction in FFS (mph; f_{LC})			
	Lanes in One Direction			
	2	3	4	>=5
>=6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

Adjustment Factor for Number of Lanes (f_N)

The values from *HCM* Exhibit 23-6 are used and based on the number of lanes in one direction. For two-way operation, the number of lanes in one direction is Data Item 34 divided by 2; for one-way facilities the value of Data Item 34 is used directly. The adjustment is made for urban freeways only; for rural facilities f_N is set to 0:

No. Lanes (One Direction; Urban Only)	**Reduction in FFS (mph; f_N)**
>= 5	0.0
4	1.5
3	3.0
2	4.5

Adjustment Factor for Interchange Density (f_{ID})

The number of interchanges is no longer available in HPMS. Therefore, an analysis of 1998 HPMS data was done to determine average interchange densities as a function of functional class and area size (Data Item 13, Rural/Urban Designation). For rural sections, interchange density is assumed not to influence free flow speed. The factor is based on the average interchange densities, as found in the 1998 HPMS data, and linear interpolation of the information in *HCM* Exhibit 23-7.

Table 2. Influence of Interchange Density on FFS

Functional Class	Area Size	Interchange Density	Interchange Adj. Factor, (f_{ID})
Urban Interstates	Small Urban	0.70	1.0
	Small Urbanized	0.76	1.3
	Large Urbanized	0.83	1.7
Other Urban Highways Qualifying as Freeways	Small Urban	0.83	1.7
	Small Urbanized	0.88	1.9
	Large Urbanized	0.91	2.1

Step 2: Calculate Base Capacity (*BaseCap*)

The Base Capacity (passenger cars per hour per lane; pcphpl) of a freeway facility is based on information found in *HCM* Exhibit 23-3. The following equations were developed based on this information:

$$\text{BaseCap} = 1{,}700 + 10\,FFS; \text{ for } FFS <= 70 \quad (2)$$

$$\text{BaseCap} = 2{,}400; \text{ for } FFS > 70$$

Step 3: Determine Peak Capacity (*PeakCap*)

The *HCM 2000* procedure does not make adjustments to the Base Capacity in order to calculate level of service and performance measures. Instead, adjustments are made to the hourly demand volume. However, for HPMS, the capacity of the segment, in terms of total vehicles per hour (vph), must be computed for a variety of analytic purposes. Therefore, the same factors used in the *HCM 2000* to adjust volume are used to adjust base capacity instead. Essentially, these adjustments convert the units from passenger cars to vehicles and lower capacity to account for the effect of heavy vehicles. The procedure is based on *HCM* Equation 23-2:

$$PeakCap = BaseCap * PHF * N * f_{HV} * f_p \quad (3)$$

Where:

$PeakCap$ = HPMS Peak Capacity (Data Item 95), vehicles per hour (all lanes, one direction)

PHF = Peak Hour Factor

N = Number of lanes in one direction

= Number of Peak Lanes (Data Item 87)

f_{HV} = Adjustment factor for heavy vehicles

f_p = Adjustment factor for driver population

Peak Hour Factor (PHF)

The Peak Hour Factor is used to account for variations in flow within the peak hour. The *HCM 2000*recommends defaults of 0.92 for urban facilities and 0.88 for rural facilities (Chapter 13). It also states that congested facilities have larger values (0.95 is "typical") than uncongested (unsaturated) ones. Clearly, these factors can have a large impact on capacity. However, determining if an HPMS section is congested is in fact a function of first determining its capacity. Therefore, an iterative process is used:

- Set PHF in Equation 3 equal to 1.0; compute peak capacity
- Determine an initial volume-to-capacity ratio (V/C), where:
    - V = AADT * K-Factor * D-Factor (Data Items 33, 85, and 86, respectively, where the K- and D-factors are expressed as decimals)
    - C = Peak Capacity
- Assign a final PHF as follows:

Table 3. PHF Assignment

Area Type	V/C Ratio	PHF
Rural	< 0.7744	0.88
	0.7744<=V/C<=0.9025	Equation (4)
	> 0.9025	0.95

Urban	< 0.8100	0.90
	0.8100<=V/C<=0.9025	Equation (4)
	> 0.9025	0.95

Where:

PHF = $(0.9025 * V/C)^{0.5}/0.95$ for special cases above (4)

Adjustment Factor for Heavy Vehicles (f_{HV})

The adjustment factor for heavy vehicles is based on calculating passenger-car equivalents for trucks and buses. (Recreational vehicles are ignored.) *HCM* Equation 23-3 and Exhibit 23-8 are used:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} \quad (5)$$

Where:

P_T = Proportion of trucks and buses in the traffic stream, expressed as a decimal (e.g., 0.15 for 15%)

= (Percent Peak Combination Trucks, Data Item 83 + Percent Peak Single Unit Trucks, Data Item 81)

E_T = Passenger-car equivalents

= 1.5 for all urban freeways

= 1.5 for rural freeways in level terrain (Data Item 70 = 1)

= 2.5 for rural freeways in rolling terrain (Data Item 70 = 2)

= 4.5 for rural freeways in mountainous terrain (Data Item 70 = 3)

Adjustment Factor for Driver Population (f_p)

For Urban Freeways, the driver population factor is set to 1.0 to indicate that drivers are familiar with roadway and traffic conditions (by virtue of the fact that most of the traffic is composed of commuters). On Rural Freeways, the factor is set to 0.975.

Appendix C AMPL Model Code

```
reset;
option solver cplex;
option cplex_options 'mipdisplay=2 mipinterval=200 ';
option show_stats 1;

# define sets
set D;
set I;
set S;
set A;
set B;
set C;
set E;
set Q;
set G;
set H;
set J;
set K;
set L;
set M;
set N;
set O;
set P;

param probability {d in D, i in I, s in S};
param replacement_cost {i in I};
param retrofit_percentage {s in S};
param capacity {i in I};
param row_hat {s in S};
param row {d in D};
param repair_cost {i in I, s in S};
param cap = 3500;

data;
set D:= d0 d1 d2 d3 d4;
set I:= i01 i02 i03 i04 i05 i06 i07 i08 i09 i10 i11 i12 i13 i14 i15 i16
i17 i18 i19 i20 i21 i22 i23 i24 i25 i26 i27 i28 i29 i30 i31 i32 i33 i34
i35 i36 i37 i38 i39 i40 i41 i42 i43 i44 i45 i46 i47 i48 i49 i50 i51 i52
i53 i54 i55 i56 i57 i58 i59 i60 i61 i62 i63 i64 i65 i66 i67 i68 i69 i70
i71 i72 i73 i74 i75 i76 i77 i78 i79;
set S:= s0 s1 s2 s3 s4;
set A:= 0 1 2 3 4 5 6 7 8 9 10 11;
set B:= 0 1 2 3 4 5 6 7 8 9 10 11;
set C:= i28 i29;
set Q:= i01 i02 i03 i04 i05 i06;
set E:= i67 i68 i69;
set G:= i13 i14 i15 i16 i17 i18 i19 i20 i21 i22 i23 i24 i25 i26 i27;
set H:= i07 i08 i09 i010 i11;
set J:= i70 i71 i72 i73 i74;
set K:= i36 i37 i38 i39 i40 i41 i42 i43 i44 i45 i46 i47 i48 i49 i50 i51
i52 i53 i54 i55 i56 i57 i58 i59;
```

```
set L:= i30 i31 i32 i33 i34 i35;
set M:= i12;
set N:= i77 i78 i79;
set O:= i75 i76;
set P:= i60 i61 i62 i63 i64 i65 i66;

read {d in D, i in I} probability [d, i, "s0"] <s0.txt;
read {d in D, i in I} probability [d, i, "s1"] <s1.txt;
read {d in D, i in I} probability [d, i, "s2"] <s2.txt;
read {d in D, i in I} probability [d, i, "s3"] <s3.txt;
read {d in D, i in I} probability [d, i, "s4"] <s4.txt;
read {i in I} capacity [i] <capacity.txt;
read {s in S} row_hat [s] <row_hat.txt;
read {i in I} replacement_cost [i] <replacement_cost.txt;
read {d in D} row [d] <row.txt;

var x {i in I, s in S} binary;
var F {a in A, b in B} >= 0;

minimize cost: sum {i in I, s in S} (x [i,s] * row_hat [s] *
replacement_cost [i]) + sum {d in D, i in I, s in S} ((1 - row [d]) *
replacement_cost [i] * probability [d,i,s] * x [i,s]);

subject to P0: F [0,1] + F [0,2] + F [0,3] + F [0,4] >= cap;

subject to P1: F [0,1] = F [1,5];

subject to P2: F [2,6] = F [0,2];

subject to P3: F [3,7] = F [0,3];

subject to P4: F [4,8] = F [0,4];

subject to P5: F [1,5] + F [6,5] = F [5,11];

subject to P6: F [6,5] + F [6,9] + F [6,7] = F [7,6] + F [2,6];

subject to P7: F [3,7] + F [6,7] = F [7,10] + F [7,8] + F [7,6];

subject to P8: F [4,8] + F [7,8] = F [8,11];

subject to P9: F [6,9] + F [10,9] = F [9,10] + F [9,11];

subject to P10: F [7,10] + F [9,10] = F [10,11] + F [10,9];

subject to P11: F [9,11] + F [5,11] + F [8,11] + F [10,11] >= cap;

subject to F2_6 {i in E}: F [2,6] <= 2 * (capacity [i] * ((sum {d in D,
s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F3_7 {i in Q}: F [3,7] <= 2 * (capacity [i] * ((sum {d in D,
s in S} probability [d,s,i] * row [d] * x [s,i])));
```

```
subject to F4_8 {i in C}: F [4,8] <=  2 * (capacity [i] * ((sum {d in
D, s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F5_11 {i in P}: F [5,11] <= 2 * (capacity [i] * ((sum {d in
D, s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F6_5 {i in K}: F [6,5] <= 2 * (capacity [i] * ((sum {d in D,
s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F7_8 {i in G}: F [7,8] <= 2 * (capacity [i] * ((sum {d in D,
s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F6_7: F [6,7] <= 3850;

subject to F7_6: F [7,6] <= 3850;

subject to F6_9 {i in J}: F [6,9] <= 2 * (capacity [i] * ((sum {d in D,
s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F7_10 {i in H}: F [7,10] <= 2 * (capacity [i] * ((sum {d in
D, s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F9_10 {i in N}: F [9,10] <=  capacity [i] * ((sum {d in D, s
in S} probability [d,s,i] * row [d] * x [s,i]));

subject to F10_9 {i in N}: F [10,9] <=  capacity [i] * ((sum {d in D, s
in S} probability [d,s,i] * row [d] * x [s,i]));

subject to F9_11 {i in O}: F [9,11] <= 2 * (capacity [i] * ((sum {d in
D, s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F10_11 {i in M}: F [10,11] <= 2 * (capacity [i] * ((sum {d
in D, s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to F8_11 {i in L}: F [8,11] <=  2 * (capacity [i] * ((sum {d in
D, s in S} probability [d,s,i] * row [d] * x [s,i])));

subject to variable {i in I}: sum {s in S} x [s,i] = 1;

solve;
```

Appendix D: Full Solution Sets

M_W 5.5 All Cost Range Solutions

Average				Q			
Throughput (Veh/hr)	Retrofit Cost ($)	Expected Damage ($)	Total Cost ($)	1	2	3	4
14377	$ 3,585,823	$ 134,823,607	$ 138,409,430	S1	S1	S1	S1
15000	$ 3,585,823	$ 134,823,607	$ 138,409,430	S1	S1	S1	S1
16500	$ 3,585,823	$ 134,823,607	$ 138,409,430	S1	S1	S1	S1
18000	$ 4,189,791	$ 134,690,615	$ 138,880,407	S1	S1	S1	S1
19500	$ 7,139,250	$ 134,037,003	$ 141,176,253	S2	S1	S1	S1
20841	$ 20,524,174	$ 132,503,334	$ 153,027,509	S4	S3	S3	S3

Low					Q		
Throughput (Veh/hr)	Retrofit Cost ($)	Expected Damage ($)	Total Cost ($)	Evaluated total cost of solution (P) ($M)	1	2	3
14377	$ 5,628,648	$ 117,021,088	$ 122,649,736	$ 136,327,339	S3	S3	S3
15000	$ 5,628,648	$ 117,021,088	$ 122,649,736	$ 136,327,339	S3	S3	S3
16500	$ 5,628,648	$ 117,021,088	$ 122,649,736	$ 136,327,339	S3	S3	S3
18000	$ 5,628,648	$ 117,021,088	$ 122,649,736	$ 136,217,849	S3	S3	S3
19500	$ 5,628,648	$ 117,021,088	$ 122,649,736	$ 138,492,878	S3	S3	S3
20841	$ 19,345,835	$ 116,530,351	$ 135,876,186	$ 148,328,354	S4	S3	S3

High					Q		
Throughput (Veh/hr)	Retrofit Cost ($)	Expected Damage ($)	Total Cost ($)	Evaluated total cost of solution (P) ($M)	1	2	3
14377	$ -	$ 141,740,829	$ 141,740,829	$ 150,092,274	S0	S0	S0
15000	$ 146,346	$ 141,676,637	$ 141,822,983	$ 150,092,274	S0	S0	S0
16500	$ 1,331,054	$ 141,120,392	$ 142,451,445	$ 150,092,274	S1	S0	S0
18000	$ 3,690,172	$ 140,560,531	$ 144,250,703	$ 159,312,178	S1	S0	S0
19500	$ 10,362,747	$ 139,270,242	$ 149,632,988	$ 168,087,283	S1	S0	S0
20841	$ 28,595,283	$ 136,813,414	$ 165,408,697	$ 187,142,586	S4	S4	S4

		H					M					
5	6	7	8	9	10	11	12	13	14	15	16	17
S1	S1	S0	S0	S1	S1	S1	S1	S0	S1	S1	S1	S1
S1	S1	S0	S0	S1	S1	S1	S1	S0	S1	S1	S1	S1
S1	S1	S0	S0	S1	S1	S1	S1	S0	S1	S1	S1	S1
S1	S1	S0	S0	S1	S1	S1	S1	S0	S1	S1	S1	S1
S1	S2	S0	S0	S3	S1	S1	S1	S0	S1	S1	S1	S1
S3	S4	S0	S0	S4	S2	S3	S1	S0	S1	S1	S1	S1

			H					M				
4	5	6	7	8	9	10	11	12	13	14	15	16
S3	S3	S3	S2	S2	S3	S3	S3	S3	S2	S3	S3	S3
S3	S3	S3	S2	S2	S3	S3	S3	S3	S2	S3	S3	S3
S3	S3	S3	S2	S2	S3	S3	S3	S3	S2	S3	S3	S3
S3	S3	S3	S2	S2	S3	S3	S3	S3	S2	S3	S3	S3
S3	S3	S3	S2	S2	S3	S3	S3	S3	S2	S3	S3	S3
S3	S3	S4	S2	S2	S4	S3	S3	S3	S2	S3	S3	S3

			H					M				
4	5	6	7	8	9	10	11	12	13	14	15	16
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S1	S0	S0	S1	S0	S0	S0	S0	S0	S0	S0
S0	S0	S1	S0	S0	S1	S0	S0	S0	S0	S0	S0	S0
S0	S1	S1	S0	S0	S4	S1	S1	S0	S0	S0	S0	S0
S4	S4	S4	S0	S0	S4	S2	S4	S0	S0	S0	S0	S0

G										C		
18	19	20	21	22	23	24	25	26	27	28	29	30
S0	S0	S0	S0	S1	S1	S1	S1	S1	S1	S1	S1	S1
S0	S0	S0	S0	S1	S1	S1	S1	S1	S1	S1	S1	S1
S0	S0	S0	S0	S1	S1	S1	S1	S1	S1	S1	S1	S1
S0	S0	S0	S0	S1	S1	S1	S1	S1	S1	S1	S1	S3
S0	S0	S0	S0	S1	S1	S1	S1	S1	S1	S1	S1	S4
S0	S0	S0	S0	S1	S1	S1	S1	S1	S1	S1	S1	S4

G											C	
17	18	19	20	21	22	23	24	25	26	27	28	29
S3	S2	S2	S2	S2	S3	S3	S3	S3	S3	S3	S3	S3
S3	S2	S2	S2	S2	S3	S3	S3	S3	S3	S3	S3	S3
S3	S2	S2	S2	S2	S3	S3	S3	S3	S3	S3	S3	S3
S3	S2	S2	S2	S2	S3	S3	S3	S3	S3	S3	S3	S3
S3	S2	S2	S2	S2	S3	S3	S3	S3	S3	S3	S3	S3
S3	S2	S2	S2	S2	S3	S3	S3	S3	S3	S3	S3	S3

G											C	
17	18	19	20	21	22	23	24	25	26	27	28	29
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S1	S1
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S1	S1

L												
31	32	33	34	35	36	37	38	39	40	41	42	43
S0	S0	S0	S0	S1	S1	S0	S0	S0	S0	S0	S0	S1
S0	S0	S0	S0	S1	S1	S0	S0	S0	S0	S0	S0	S1
S0	S0	S0	S0	S1	S1	S0	S0	S0	S0	S0	S0	S1
S0	S0	S0	S0	S1	S1	S0	S0	S0	S0	S0	S0	S1
S0	S0	S0	S0	S1	S1	S0	S0	S0	S0	S0	S0	S1
S0	S0	S0	S0	S1	S1	S0	S0	S0	S0	S0	S0	S1

L												
30	31	32	33	34	35	36	37	38	39	40	41	42
S3	S2	S2	S2	S2	S3	S3	S2	S2	S2	S2	S2	S2
S3	S2	S2	S2	S2	S3	S3	S2	S2	S2	S2	S2	S2
S3	S2	S2	S2	S2	S3	S3	S2	S2	S2	S2	S2	S2
S3	S2	S2	S2	S2	S3	S3	S2	S2	S2	S2	S2	S2
S3	S2	S2	S2	S2	S3	S3	S2	S2	S2	S2	S2	S2
S4	S2	S2	S2	S2	S3	S3	S2	S2	S2	S2	S2	S2

L												
30	31	32	33	34	35	36	37	38	39	40	41	42
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S1	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S1	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S2	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S4	S0	S0	S0	S0	S1	S0	S0	S0	S0	S0	S0	S0
S4	S0	S0	S0	S0	S1	S0	S0	S0	S0	S0	S0	S0

K												
44	45	46	47	48	49	50	51	52	53	54	55	56
S1	S1	S1	S0	S0	S0	S0	S0	S1	S0	S0	S0	S1
S1	S1	S1	S0	S0	S0	S0	S0	S1	S0	S0	S0	S1
S1	S1	S1	S0	S0	S0	S0	S0	S1	S0	S0	S0	S1
S1	S1	S1	S0	S0	S0	S0	S0	S1	S0	S0	S0	S1
S1	S1	S1	S0	S0	S0	S0	S0	S1	S0	S0	S0	S1
S1	S1	S1	S0	S0	S0	S0	S0	S1	S0	S0	S0	S1

K												
43	44	45	46	47	48	49	50	51	52	53	54	55
S3	S3	S3	S3	S2	S2	S2	S2	S2	S3	S2	S2	S2
S3	S3	S3	S3	S2	S2	S2	S2	S2	S3	S2	S2	S2
S3	S3	S3	S3	S2	S2	S2	S2	S2	S3	S2	S2	S2
S3	S3	S3	S3	S2	S2	S2	S2	S2	S3	S2	S2	S2
S3	S3	S3	S3	S2	S2	S2	S2	S2	S3	S2	S2	S2
S3	S3	S3	S3	S2	S2	S2	S2	S2	S3	S2	S2	S2

K												
43	44	45	46	47	48	49	50	51	52	53	54	55
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0

			P							E		
57	58	59	60	61	62	63	64	65	66	67	68	69
S1	S0	S0	S0	S0	S1	S1	S1	S0	S0	S1	S1	S1
S1	S0	S0	S0	S0	S1	S1	S1	S0	S0	S1	S1	S1
S1	S0	S0	S0	S0	S1	S1	S1	S0	S0	S1	S1	S1
S1	S0	S0	S0	S0	S1	S3	S1	S0	S0	S1	S1	S1
S1	S0	S0	S0	S0	S1	S3	S1	S0	S0	S3	S1	S1
S1	S0	S0	S0	S0	S1	S4	S1	S0	S0	S4	S2	S2

				P							E	
56	57	58	59	60	61	62	63	64	65	66	67	68
S3	S3	S2	S2	S2	S2	S3	S3	S3	S2	S2	S3	S3
S3	S3	S2	S2	S2	S2	S3	S3	S3	S2	S2	S3	S3
S3	S3	S2	S2	S2	S2	S3	S3	S3	S2	S2	S3	S3
S3	S3	S2	S2	S2	S2	S3	S3	S3	S2	S2	S3	S3
S3	S3	S2	S2	S2	S2	S3	S3	S3	S2	S2	S3	S3
S3	S3	S2	S2	S2	S2	S3	S4	S3	S2	S2	S4	S3

				P							E	
56	57	58	59	60	61	62	63	64	65	66	67	68
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S1	S0	S0	S0	S1	S0
S0	S0	S0	S0	S0	S0	S0	S4	S1	S0	S0	S1	S0
S0	S0	S0	S0	S0	S0	S0	S4	S1	S0	S0	S4	S1
S0	S0	S0	S0	S0	S0	S0	S4	S1	S0	S0	S4	S2

J					O		N		
70	71	72	73	74	75	76	77	78	79
S1	S1	S1	S0	S0	S1	S0	S1	S1	S1
S1	S1	S1	S0	S0	S1	S0	S1	S1	S1
S1	S1	S1	S0	S0	S1	S0	S1	S1	S1
S1	S1	S1	S0	S0	S1	S0	S1	S1	S1
S1	S1	S2	S0	S0	S1	S0	S1	S1	S1
S3	S3	S4	S0	S0	S1	S0	S1	S1	S1

	J					O		N		
69	70	71	72	73	74	75	76	77	78	79
S3	S3	S3	S3	S2	S2	S3	S2	S3	S3	S3
S3	S3	S3	S3	S2	S2	S3	S2	S3	S3	S3
S3	S3	S3	S3	S2	S2	S3	S2	S3	S3	S3
S3	S3	S3	S3	S2	S2	S3	S2	S3	S3	S3
S3	S3	S3	S3	S2	S2	S3	S2	S3	S3	S3
S3	S3	S3	S4	S2	S2	S3	S2	S3	S3	S3

	J					O		N		
69	70	71	72	73	74	75	76	77	78	79
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S1	S0	S0	S0	S0	S0	S0	S0
S2	S0	S0	S1	S0	S0	S0	S0	S0	S0	S0
S2	S4	S4	S4	S0	S0	S2	S0	S0	S0	S0

M_W 7.0 All Costs Range Solutions

Average				Q		
Throughput (Veh/hr)	Retrofit Cost ($)	Expected Damage ($)	Total Cost ($)	1	2	3
2000	$ 16,730,701	$ 332,232,542	$ 348,963,243	S1	S1	S1
4000	$ 16,730,701	$ 332,232,542	$ 348,963,243	S1	S1	S1
6000	$ 16,730,701	$ 332,232,542	$ 348,963,243	S1	S1	S1
8000	$ 17,860,141	$ 331,835,079	$ 349,695,220	S1	S1	S1
10000	$ 23,181,130	$ 330,371,482	$ 353,552,612	S2	S1	S1
11828	$ 55,986,737	$ 324,745,624	$ 380,732,361	S4	S4	S4

Low						
Throughput (Veh/hr)	Retrofit Cost ($)	Expected Damage ($)	Total Cost ($)	Evaluated total cost of solution (P) ($M)	1	2
2000	$ 12,413,101	$ 295,317,569	$ 307,730,670	$ 339,248,643	S3	S3
4000	$ 12,413,101	$ 295,317,569	$ 307,730,670	$ 339,248,643	S3	S3
6000	$ 12,413,101	$ 295,317,569	$ 307,730,670	$ 339,248,643	S3	S3
8000	$ 12,413,101	$ 295,317,569	$ 307,730,670	$ 338,849,047	S3	S3
10000	$ 13,496,281	$ 295,265,949	$ 308,762,230	$ 339,678,211	S3	S3
11828	$ 43,503,390	$ 293,805,699	$ 337,309,090	$ 363,496,792	S4	S4

High						
Throughput (Veh/hr)	Retrofit Cost ($)	Expected Damage ($)	Total Cost ($)	Evaluated total cost of solution (P) ($M)	1	2
2000	$ -	$ 369,147,146	$ 369,147,146	$ 403,472,946	S0	S0
4000	$ 146,346	$ 369,223,883	$ 369,370,229	$ 403,472,946	S0	S0
6000	$ 4,772,609	$ 366,071,786	$ 370,844,396	$ 403,472,946	S1	S1
8000	$ 9,289,860	$ 365,258,141	$ 374,548,001	$ 410,443,006	S1	S1
10000	$ 34,018,296	$ 354,881,429	$ 388,899,725	$ 429,831,055	S1	S1
11828	$ 75,631,436	$ 348,178,859	$ 423,810,296	$ 495,536,220	S4	S4

			H					M				
4	5	6	7	8	9	10	11	12	13	14	15	16
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S2	S1	S1	S2	S2	S2	S1	S1	S1	S1	S1
S4	S4	S4	S1	S1	S4	S4	S4	S3	S1	S1	S1	S1

Q				H					M			
3	4	5	6	7	8	9	10	11	12	13	14	15
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S4	S4	S4	S4	S3	S3	S4	S4	S4	S3	S3	S3	S3

Q				H					M			
3	4	5	6	7	8	9	10	11	12	13	14	15
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S1	S1	S1	S1	S0	S0	S1	S1	S1	S0	S0	S0	S0
S1	S1	S1	S1	S0	S0	S1	S1	S1	S0	S0	S0	S0
S1	S1	S1	S1	S0	S0	S1	S1	S1	S1	S0	S0	S0
S4	S4	S4	S4	S0	S0	S4	S4	S4	S4	S0	S0	S0

G											C	
17	18	19	20	21	22	23	24	25	26	27	28	29
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S3	S3
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S3	S3

G												
16	17	18	19	20	21	22	23	24	25	26	27	28
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3

G												
16	17	18	19	20	21	22	23	24	25	26	27	28
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S2
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S2
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S4

L												
30	31	32	33	34	35	36	37	38	39	40	41	42
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S3	S1	S1	S1	S1	S2	S1	S1	S1	S1	S1	S1	S1
S4	S1	S1	S1	S1	S3	S1	S1	S1	S1	S1	S1	S1
S4	S1	S1	S1	S1	S4	S1	S1	S1	S1	S1	S1	S1

	L											
29	30	31	32	33	34	35	36	37	38	39	40	41
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S4	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S4	S3	S3	S3	S3	S4	S3	S3	S3	S3	S3	S3

	L											
29	30	31	32	33	34	35	36	37	38	39	40	41
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S1	S0	S0	S0	S0	S1	S0	S0	S0	S0	S0	S0
S0	S2	S0	S0	S0	S0	S1	S0	S0	S0	S0	S0	S0
S2	S4	S0	S0	S0	S0	S4	S0	S0	S0	S0	S0	S0
S2	S4	S0	S0	S0	S0	S4	S0	S0	S0	S0	S0	S0
S4	S4	S0	S0	S0	S0	S4	S0	S0	S0	S0	S0	S0

K												
43	44	45	46	47	48	49	50	51	52	53	54	55
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1

K												
42	43	44	45	46	47	48	49	50	51	52	53	54
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3

K												
42	43	44	45	46	47	48	49	50	51	52	53	54
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0

				P							E	
56	57	58	59	60	61	62	63	64	65	66	67	68
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S3	S2	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S2	S4	S3	S1	S1	S3	S3
S1	S1	S1	S1	S1	S1	S2	S4	S3	S1	S1	S4	S4

					P							
55	56	57	58	59	60	61	62	63	64	65	66	67
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S4	S3	S3	S3	S4

					P							
55	56	57	58	59	60	61	62	63	64	65	66	67
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S1	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S1	S0	S0	S0	S1
S0	S0	S0	S0	S0	S0	S0	S1	S2	S1	S0	S0	S1
S0	S0	S0	S0	S0	S0	S0	S2	S4	S4	S1	S1	S4
S0	S0	S0	S0	S0	S0	S0	S2	S4	S4	S1	S1	S4

	J					O		N		
69	70	71	72	73	74	75	76	77	78	79
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
S3	S2	S2	S2	S1	S1	S1	S1	S1	S1	S1
S4	S4	S4	S4	S1	S1	S4	S1	S1	S1	S1

E		J					O		N		
68	69	70	71	72	73	74	75	76	77	78	79
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3	S3
S4	S4	S4	S4	S4	S3	S3	S4	S3	S3	S3	S3

E		J					O		N		
68	69	70	71	72	73	74	75	76	77	78	79
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0
S1	S1	S1	S1	S1	S0	S0	S1	S0	S0	S0	S0
S1	S1	S1	S1	S1	S0	S0	S1	S0	S0	S0	S0
S4	S1	S4	S4	S4	S0	S0	S4	S0	S0	S0	S0
S4	S4	S4	S4	S4	S0	S0	S4	S0	S0	S0	S0