METHOD FOR PRIORITIZING HIGHWAY ROUTES FOR RECONSTRUCTION AFTER A NATURAL DISASTER

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Memphis

Sandy A. Mehlhorn

December 2009

Dedication

This research is dedicated to my family. Without their love, encouragement, patience and understanding the last few years I would not have been able to complete this work.

Abstract

Mehlhorn, Sandy A., Ph.D, The University of Memphis. December 2009. Method for Prioritizing Highway Routes for Reconstruction after a Natural Disaster. Major Professor: Dr. Martin Lipinski.

The Federal Emergency Management Agency (FEMA) has identified the four phases of disaster related planning as mitigation, preparation, response and recovery. Considerable emphasis has been placed on evacuation plans and first response after a disaster. However, research is lacking in the recovery phase. The recovery phase is characterized by activity to return life to normal or improved levels. FEMA defines recovery as the restoration of transportation components to their condition prior to the event. This research considers the recovery phase, which encompasses restoring services and rebuilding disaster stricken areas of the highway transportation network. It is assumed that evacuation, minor repairs/cleanup for emergency personnel and delivery of supplies has already been accomplished in the response phase. The purpose of this research is to provide criteria for prioritizing the reconstruction of highway networks. This is accomplished through the use of a mathematical model. This model provides a method for state and local transportation agencies or planners to develop a specific plan for reconstructing roadways for long term use. The model developed in this research provides a framework for decision-making for long-term recovery of highway networks. The model can be used for planning or after a disaster has occurred. This research is different from previous research in that actual paths are chosen for reconstruction.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

The Federal Emergency Management Agency (FEMA) has identified the four phases of disaster related planning as mitigation, preparation, response and recovery. Considerable emphasis has been placed on the preparation and response phases through evacuation plans and first response after a disaster (Cova and Church 1997, Kovel 2000, Sakakibara, Kajitani and Okada 2004). However, research is lacking in the recovery phase. The recovery phase is characterized by activity to return life to normal or improved levels (T. Cova 1999). FEMA defines recovery as the restoration of transportation components to their condition prior to the event. This research considers the recovery phase, which encompasses restoring services and rebuilding disaster stricken areas of the highway transportation network. It is assumed that evacuation, minor repairs/cleanup for emergency personnel and delivery of supplies has already been accomplished in the response phase. The purpose of this research is to develop the initial methodology needed to provide a mechanism for prioritizing the reconstruction of highway networks. This is accomplished through the use of a single objective mathematical model with multiple constraints. The model will serve as a preliminary framework for future studies incorporating additional parameters or an alternative benefit definition. This model serves as a tool for state and local transportation agencies or planners to develop a specific plan for reconstructing roadways for long-term use.

The framework for decision-making provided by the model is an important first step in developing a recovery plan. A recovery plan gives transportation officials the advantage of a more efficient recovery time after a disaster. This is achieved through identifying routes of highest priority for reconstruction such that major roadways are incapacitated for shorter times. The identification of high-priority roadways is important because money can be directed toward maintenance and retrofitting along these roadways so that they are at less risk for major damage in the event of a disaster. This identification is accomplished during the preparedness phase so that the maintenance performed can further reduce the recovery time after a disaster.

Current Recovery Phase Research

Current research for rebuilding of the highway network during the recovery phase is limited. Most of the research does not address developing an actual strategy for reconstructing the network for long term use. One study in 2002 established a mathematical model for comparing restoration strategies in the urban area of Seattle, Washington. The author developed an approach to post-disaster restoration of highway networks with performance measured in terms of transportation accessibility to the regional population (Chang 2003). Another study performed involved the short term repair of roadways for relief distribution. This research focused on repairs sufficient for disaster relief work and was not intended for long term repairs for restoration of the highway network (Yan and Shih 2008).

The United States Department of Transportation (USDOT) has recognized the need for research in the area of transportation recovery (United States Department of Transportation 2009). To help fill the information void in the recovery phase, the USDOT has undertaken development of a National Transportation Recovery Plan (NTRP), which is slated for completion in 2010. The NTRP will be a guide for transportation officials on the local and state level to build a coordinated, efficient transportation recovery plan that "focuses on restructuring transportation systems to an increased level of resiliency to protect against future disasters" (United States Department of Transportation 2008) (United States Department of Transportation 2008). The USDOT states that recovery models must use pre-existing data available to local authorities as inputs in order to be effective. Suggested sources of data are commonly produced commerce and traffic congestion models and critical infrastructure risk analysis data previously produced for the U.S. Department of Homeland Security or the Federal Emergency Management Agency. In light of this recommendation, the current research uses common sources of data as inputs to the model.

GIS Applications in Recovery Plans

Planning is an important part of an effective recovery plan. For areas with little historical data on natural disasters, this planning can be very difficult because the exact damage levels are not easily predictable. There are software packages available that can be used to predict damage and can be used for planning purposes. Some of these software packages are HAZUS-MH (National Institute of Building Sciences 2008) and REDARS (ImageCat, Inc. 2005).

HAZUS-MH (Hazards United States-Multi-hazard) has been shown effective for estimating damage to transportation networks after a natural disaster. HAZUS-MH was developed by the Federal Emergency Management Agency (FEMA). HAZUS-MH uses GIS (Geographic Information Systems) to graphically depict hazard data, economic losses and building and infrastructure damage from earthquakes, hurricanes, and floods. The software combines hazard layers with national databases and applies both loss estimation and risk assessment methodologies (National Institute of Building Sciences 2008). Output given by HAZUS-MH includes the likely effects of the natural disaster based on a set of characteristics that can be input by the user or from default databases such as the United States Geological Survey (USGS) maps and statistical analysis of the inventories in the database. Output information is also given for estimates of the effects in five main areas: damage, functionality, economic, social, and system performance (Lawson, Jawhar and Humphrey 2004). The output for the model developed by the current research follows the same format as the output from HAZUS-MH. Also, some of the cost information from the HAZUS-MH database is used for this research.

REDARS (**R**isks due to **E**arthquake **D**amage to **R**oadway **S**ystems) is similar to HAZUS-MH in calculating damage assessment to roadways and transportation components given a certain earthquake scenario. Databases in REDARS containing time for repairs of damaged transportation components and ratio of replacement values for repair of damaged transportation components is used in this research.

Both HAZUS-MH and REDARS use GIS. GIS is becoming an integral tool in supporting damage assessment, network prioritization, and public education after a disaster (T. Cova 1999). Three GIS software packages are used in this research: HAZUS-MH, REDARS and ArcGIS. The final GIS software ArcGIS, is used for calculating paths as well as visual reference of the locations of critical facilities. Geographic Information Systems (GIS) is ideal for use in this application because of ease in handling extensive databases and the ability to visually evaluate highway networks.

Economic Impacts of Natural Disasters

Studies have revealed that the extent of damage to transportation systems and the speed of its restoration are critical determinants of how quickly a disaster stricken area can recover (Chang 2003). Experience has shown that the effects of disasters on highway components not only disrupt traffic flows, but the economic recovery is also impacted (Werner, et al. 2000). After the 1994 earthquake that hit the San Fernando Valley near the community of Northridge, research was performed to determine the economic impacts of freeway damage. The study, using a survey approach, found that 43% of all firms reporting any losses mentioned that some of those losses were because of transportation problems (Boarnet 1996). It is evident that there is a direct relationship between the recovery of the transportation network and the economic recovery of an area.

Development of model

When developing a model for long-term repairs of a transportation network, several things must be considered. Questions to be answered include: which entities should be given priority for accessibility (i.e. hospitals, residential areas, businesses), how much money will be available for the repairs, and what length of time will be required for repairs. Consideration should also be given to the availability of information that is to be input in the model. As is suggested in the USDOT document, the information should be readily available to the state and local agencies who will be implementing the model. All of these factors must be taken into account.

This research only considers the highway networks and the corresponding transportation components (i.e. overpasses, bridges, roadways, tunnels, etc.). Highways were considered for this research because they are a public good, available to all people without rivalry or exclusions. Like most public goods, the burden for funding highways is on the taxpayers unlike railroads which are a private industry. If a plan for the reconstruction of highways is completed, businesses can use them for shipping freight, as well as serving passenger car use for traveling to work, shopping and other purposes. For the current research, the highway network was divided into “paths” or sections of roadways. Each path could contain any number of transportation components. By dividing the network into various routes or “paths” as opposed to individual transportation components, the cost of a path will be the combined cost of the repair of all the transportation components within that path. Also a benefit could be assigned to a path once it is completed. This benefit is very important in prioritizing the paths for reconstruction because it allows a weighting factor for certain locations of greater importance to the vitality and recovery of the area. Since priority is being given to business continuity for this research, the associated benefit is the fiscal year revenue. Another example of a benefit could be the number of hospital beds if hospitals are given the priority for reconstruction of the highway network. A path is defined for this research as beginning at a business and ending at the edge of the perimeter of damage. The model is easily adaptable to allow various scenarios that meet the different regional priorities.

Demonstration of Model in Shelby County, Tennessee

The model was applied using the transportation network in Shelby County, Tennessee. Shelby County was chosen as the study region for this research because of its importance to the economic vitality of the Midwest region of the country (Commerce 2006). At the heart of Shelby County is the metropolitan area of Memphis, which includes the city of Memphis. Shelby County is home to five class one railroads, the largest cargo airport in the country and over 100 warehouses for major retailers such as Nike, DVD distributors and others. Over 150 metropolitan markets can be reached by truck overnight from Shelby County. In 2007, over 11 million tons of freight originated or terminated at the International Port of Memphis (Global Insight 2009). If a significant event were to occur that crippled the transportation system, the economic effects would be far reaching and have national implications. Given the importance of industry to the economic vitality of the Shelby County region, key businesses were given priority for reconstruction of the highway system. The key businesses were defined as the top 25 revenue producing industries in Shelby County. This information was obtained from the Memphis Business Journal for the 2007 fiscal year (Bolton 2008). As stated earlier, highways are the only transportation mode considered for this research. This is especially important to Shelby County because of the large amount of freight traffic on the highways in the region. As reported in the 2007 Commodity Flow Survey, manufacturing establishments shipped more than 5.3 billion tons of commodities and trucks carried 70.7% of the total value of all the commodities shipped (Bureau 2007). However, different regions could choose other entities for priority highway accessibility. For example, some regions could choose to give priority to restored access to hospitals or residential areas and the model would still be valid for such purposes.

Summary

Many studies have estimated damage from disasters but this research uses those damage estimates to determine a plan for reconstruction of the highway network. The current model only considers the highway network and corresponding transportation components. Future research could be conducted to include other aspects of freight traffic including rail and barge facilities. The model is designed to be used in the recovery phase after first response and evacuations have been completed.

This research is an important first step in establishing a recovery plan for state and local transportation and planning agencies. It is expected that the model developed from this research can be used by transportation agencies for disaster preparedness and mitigation planning, and for prioritizing maintenance and retrofitting of transportation components in the system based upon their importance to regional accessibility after a disaster. The model could also be used by transportation agencies in the event of an actual disaster for prioritizing the reconstruction of roadways to allow the most highway accessibility to key facilities.

Chapter 2

Literature Review

Although significant emphasis has been placed in recent research on evacuation plans and first response after a disaster, research is lacking in the recovery phase. The recovery phase takes place after emergency personnel and evacuation has taken place. The basis of this research is dependent upon four parts: 1) review of existing recovery phase models to determine if another one is needed, 2) damage estimations after a natural disaster, 3) economic impacts of natural disasters, and 4) constructing a model for the long-term reconstruction of the highway network.

Review of Existing Recovery Phase Models

Research performed in 2002 established a mathematical model for comparing restoration strategies in the urban area of Seattle, Washington (Chang 2003). The author developed an approach for post-disaster restoration of highway networks with performance measured in terms of transportation accessibility to the regional population. The region was defined by a 25 mile radius around the Seattle urban area. Two different strategies were compared for repairing highway networks to allow the greatest concentrations of the population in and out of the urban area. The first strategy evaluated was the repair of the least physically damaged areas to the most severely damaged areas. The second strategy was to repair an entire route irrespectively of the damage state of the route. The second strategy was shown to provide better accessibility to the largest portion of the general population. The mathematical model used for comparing the two strategies measured accessibility loss in terms of changes to modeled travel times rather than in terms of approximated travel distances. The model also incorporated distance-decay effects. The author suggested that further research was needed in refining the model with respect to post-disaster changes in origin-destination flows, destination opportunities and mode choice. Also recommended was further research into the technical and resource constraints on transportation repair and restoration in actual disaster situations (Chang 2003).

Similar research to the one presented by Chang (2003) was proposed by Sakakibara et al. (2004) where a topological index was used to quantify road network dispersiveness/concentration in a disaster situation and prevent isolating city districts for evacuation. The most robust network was defined as the network that minimized the isolation of districts in a catastrophic disaster. The topological index was calculated based on the various links and nodes representing a given road network structure. A larger topological index meant a more dispersed road network. A dispersed road network is less likely to cause isolation of districts in a disaster because it provides more possibilities of connection with neighboring districts than a concentrated network. This method was applied to a highway network in the Hanshin region of Japan. For the study, nodes were defined as municipalities that have their own facilities to service the daily needs of its citizens. Links were defined as the highways that connect the various municipalities. The authors determined that the topological index was a valuable tool for evaluating the possibility of node isolation. One fact was that the topological index values can vary based on the number of nodes in a highway network. Further research was recommended in standardizing the topological index and the definition of nodes (Sakakibara, Kajitani and Okada 2004).

Another study for rural roadway networks developed a model with the objective of minimizing the length of time for emergency repair and relief distribution with the shortest possible period of time (Yan and Shih 2008). This research admittedly was not concerned with long-term repairs. The model solved a multi-objective mixed-integer multi-commodity network flow problem. The constraints of the model were flow conservation constraints and seven types of operational constraints on the arc flows. The model was tested on a highway network in Taiwan. Then, to assess the robustness of the model, several fictitious roadway networks were generated and evaluated. The fictitious networks were categorized as branching pattern, web pattern and grid network (Yan and Shih 2008).

Research performed in Japan studied the feasibility of using Genetic Algorithms to optimize the restoration process of lifeline networks after an earthquake (Sato and Ichii 1995). The research established an index to measure the efficiency of the restoration process that would be minimized to provide the restoration time of each damaged component in the network. As an application to a road network, the authors applied the restoration index to travel times of vehicles. An assumption used in the model was that the initial stage was at the completion of emergency repairs with traffic flowing at each link at a minimum level. The optimization was the restoration process to reduce the inconvenience of delayed travel times of the damaged road network (Sato and Ichii 1995). This model was fairly effective although it was a static assignment model.

Need for another model

The United States Department of Transportation (USDOT) is currently undertaking the development of a National Transportation Recovery Plan (NTRP) to assist communities in the recovery process and to fill the information void for this phase of disaster recovery. As part of Phase II of the NTRP, an empirical formula will be derived for the prioritization of transportation recovery. The USDOT states that the model must use pre-existing data available to local authorities as inputs in order to be effective. Suggested sources of data are commonly produced commerce and traffic congestion models and critical infrastructure risk analysis data previously produced for Department of Homeland Security or Federal Emergency Management Agency. For the NTRP, the USDOT has the goal of providing a formula flexible enough to be applied to both small and catastrophic events and that will be easily understood by untrained users (United States Department of Transportation 2008). The model for the current research will incorporate some of the same criteria as the USDOT document. The model will be a multi-objective optimization problem that incorporates inputs from databases that are easily accessible for state and local agencies. The model will allow specific routes to be chosen for reconstruction based on a set of criteria determined by the user. The criteria for this research include giving priority to local industry in order to speed the economic recovery of a disaster stricken area.

Damage Estimations for Transportation Networks

The previous literature reviews discuss different models for routing traffic through post-disaster highway networks that will most likely be damaged and broken into isolated components. When such a model is being developed, a significant amount of data is needed about the highway network. Three key elements should be considered for an effective post-disaster model. These elements are key facilities to be evaluated, resources available for response operations and their location, and the extent of likely damage to these facilities (Kovel 2000). When considering the rebuilding of the highway network after a disaster, key facilities would include bridges, tunnels and roadways. These components are part of the transportation lifeline. These “lifelines” also include electricity and other utilities that are crucial in sustaining social and economic systems. Bridges have been repeatedly shown to be the most vulnerable component of the highway system (Hwang, Jernigan and Lin 2000). There are 483,621 bridges on National Highway System roads in the United States (Federal Highway Administration 2008). This number does not take into account bridges on locally maintained roads and streets. Evaluation of bridges is critical because they are a weakness for widespread transportation discontinuity for people, especially in urban areas.

The vulnerability of bridges in an earthquake has been studied extensively. A procedure developed for bridges in Shelby County, Tennessee determined the peak ground acceleration (PGA), or amount of ground shaking, for the various bridge sites and fragility curves for the type of bridge to determine the probability that the bridge sustained no/minor, repairable or significant damage (Hwang, Jernigan and Lin 2000). The study determined that out of 452 Shelby County bridges evaluated, 160 bridges are expected to sustain significant damage, 136 bridges are expected to sustain repairable damage and 156 bridges will sustain minor or no damage (Hwang, Jernigan and Lin 2000).

Use of GIS in damage estimation

GIS is becoming an integral part of supporting damage assessment, rebuilding and public education after a disaster (T. Cova 1999). The use of GIS software is ideal for handling all of the data necessary for modeling after a natural disaster because an extensive database, including information such as system facilities, year they were built and current condition, is needed. The visualization capabilities also make GIS ideal for natural disaster modeling. A database should be able to integrate all of the information and to establish relationships between various attribute data and key infrastructure features (Pradhan, Laefer and Rasdorf 2007). Programs such as REDARS (Risks due to Earthquake Damage to Roadway Systems) and HAZUS-MH (Hazards United States-Multi-hazard) use GIS mapping that allows locations of key facilities to be overlaid with damage estimates for quick visual reference.

REDARS uses a procedure for evaluating bridges with a risk-based methodology to estimate not only bridge damage but also post-earthquake traffic flows and travel times (Werner, et al. 2000). Model input is a GIS database consisting of four modules that characterize the transportation network, seismic hazards, component vulnerabilities, and economic factors pertaining to highway system damage. For this seismic risk analysis there are two possible methods to choose from. The first is a user-equilibrium method which assumes all drivers follow routes that minimize their travel times. This method is an exact mathematical solution to an idealized model of driver behavior. The second method is a probabilistic method of associative memory analysis. This method is a heuristic approach that is GIS compatible, uses information readily available from Metropolitan Planning Organizations and provides rapid estimation of network flows. The model was tested on the highway system in Shelby County, Tennessee (Werner, et al. 2000). Unlike the first model discussed for this region, this application was performed on a transportation network consisting of 384 bridges in Shelby County, Tennessee. REDARS was released to the public in March 2006. The research for the product was funded by the Federal Highway Administration. Key features of the software include estimates of impact on traffic flow and travel time after an earthquake, estimates of economic losses as a function of travel delay, bridge damage estimates and resulting congestion, and ground motion estimates for actual and scenario earthquake events (ImageCat, Inc. 2005). The software was tested for the Los Angeles, California area. The results were similar to the Shelby County, Tennessee results (Werner, et al. 2000).

Another GIS based software that has been shown effective for estimating damage to transportation networks after a natural disaster is HAZUS-MH (Hazards United States-Multi-hazard). HAZUS-MH was developed by the Federal Emergency Management Agency (FEMA). The software can be obtained free of charge from the FEMA website (http://www.fema.gov/plan/prevent/hazus/index.shtm). HAZUS-MH uses GIS to graphically depict hazard data, economic losses, and building and infrastructure damage from earthquakes, hurricanes, and floods. The software combines hazard layers with national databases and applies both loss estimation and risk assessment methodologies (National Institute of Building Sciences 2008). Geographic information stored in the GIS database includes building inventories, critical facilities such as hospitals, transportation systems and utilities (Pradhan, Laefer and Rasdorf 2007). The software was originally designed to assist emergency management agencies in estimating the effects from earthquakes but its capabilities have expanded to encompass hurricanes and floods as well. Output given by HAZUS-MH includes the likely effects of the natural disaster based on a set of characteristics that can be input by the user or obtained from default databases such as the United States Geological Survey (USGS) maps and statistical analysis of the inventories in the database. Output information is also given for estimates of the effects in five main areas: damage, functionality, economic, social, and system performance (Lawson, Jawhar and Humphrey, Predicting Consequences 2004).

Another GIS software, ArcGIS, is also used in this research. ArcGIS is an integrated collection of GIS products that are used for spatial analysis, data management, and mapping (ESRI 2008). ArcGIS is the platform used for mapping businesses, roadways, location of transportation facilities and paths for this research.

Widespread use of GIS by emergency management agency's, due to more affordable technologies, can enhance the efficiency and productivity of their efforts. A case study of the Douglas County Emergency Management Agency (DCEMA) in Kansas was initiated to develop a tool to maintain an integrated emergency management system that would enable the emergency manager to visualize and analyze natural disaster situations more accurately. The study focused on flooding, which is the biggest natural disaster threat to that area. DCEMA used a GIS database to collect information on the land data such as hydrography and topography to derive data such as flood zones. This information was then overlaid with facilities in the county to determine what facilities would be threatened in an actual flood situation. The study was successful in providing information to the emergency manager for visualizing potential problems in order to improve response and decrease risk to life and property. An advantage to the study was that the database can now be used to determine risks from other disasters. DCEMA plans to use the database to model hazardous materials spills and large blasts from facilities such as chemical plants (Gunes and Kovel 2000).

Economic Impacts from Natural Disasters

Impacts from a natural disaster have a widespread effect on the economy of that area. Experience has shown that the effects of disasters on highway components not only disrupt traffic flows, but the economic recovery is also impacted (Werner, et al. 2000). Physical damage to housing and lifeline services can lead to indirect economic losses due to business disruption (Guha n.d.). Research has been performed to determine the extent of these indirect losses. One such study uses a variation of the Southern California Planning Model version 1 (SCPM1) (Cho, et al. 2001). The SCPM1 was developed for the five-county Los Angeles metropolitan region. It is an integrated modeling approach that incorporates input-output and spatial allocation. The approach allows the representation of estimated spatial and sectoral impacts corresponding to any vector changes in final demand. The model was applied to a hypothetical earthquake on the Elysian Park blind thrust fault in Los Angeles, California. For this particular research, improvements were made to the SCPM1 model to include the regional transportation network. The new version is called SCPM2. The model's approach is to use ABSG Consulting, Inc.'s program called EPEDAT (Early Post-Earthquake Damage Assessment Tool) to determine structural damage and predict the lengths of time for which firms throughout the region will be nonoperational. The input-output model translates this information into direct, indirect and induced costs. The indirect and induced costs are spatially allocated in terms consistent with the transportation behaviors of firms and households. Using a conservative bridge closure criteria, the model showed a cost of approximately $42 billion in structure loss excluding bridges. This is the estimated cost to repair or replace structures damaged in the earthquake. A total transportation cost of nearly $69 billion was estimated. A value of time for individuals of $6.50 per hour and $35 per hour for freight was used in the model (Cho, et al. 2001).

After the 1994 earthquake that hit the San Fernando Valley near the community of Northridge, research was performed to determine the economic impacts of freeway damage. The research, using a survey approach, found that 43% of all firms reporting any losses mentioned that some of those losses were because of transportation problems (Boarnet 1996). Another study emphasizing indirect costs, applied inter-industry models to measure regional economic impact (Cho, et al. 2001). The authors traced and recorded the inter-sectoral ripple effects associated with the full impacts of electricity disruptions after a hypothetical earthquake in Memphis, Tennessee. Over the first 15 weeks after the event, a 7% loss of Gross Regional Product was forecasted (Cho, et al. 2001).

Impacts from a natural disaster affect not only the local economy but also the regional economy. A model to estimate and evaluate the economic impacts from a catastrophic earthquake should consider, at a minimum, the interregional commodity flows, regional input-output relationships and corresponding transportation network flows. One such model was implemented for the U.S. highway and railway networks to forecast flows of 11 commodity sectors in the New Madrid Seismic Zone (Ham, Kim and Boyce 2004). The model estimated increased shipment lengths up to 40 miles due to disruptions in the transportation network due to a catastrophic earthquake. The model is a constrained optimization problem solved by a partial linearization algorithm. The author suggested the results be used to identify critical sections of the network and analyze post-event reconstruction strategies (Ham, Kim and Boyce 2004).

Construction of a new model

The term modeling can mean different things to different people. There are basically two types of modeling that can be done in terms of transportation: simulation and mathematical. Simulation modeling attempts to portray a system over time to visualize interactions within the system. Mathematical modeling is a representation of a system at a particular point in time. Many types of transportation simulation models are available including TransCAD and Paramics. These software can be previewed at their websites: www.caliper.com and www.paramics-online.com, respectively. There are also many variations of mathematical models for transportation applications. These models are usually edited to suit the user's particular need. This research develops a mathematical model for prioritizing roadways for reconstruction after a natural disaster. For this reason, various existing mathematical modeling techniques will be discussed.

Overview of Transportation Models

Dynamic Traffic Assignment (DTA) is a method for solving problems such as the one in this research. DTA refers to a broad range of problems that deal with time-varying traffic flows versus static assignment problems. DTA methods are preferred over static methods for this reason. DTA problems have varying data requirements and capabilities in terms of representing the traffic system with corresponding decision variables. Currently there is not a single DTA model that provides a universal solution for general networks. Each DTA is designed based on the needs of the model. Different types of DTA models have their own benefits and challenges. Mathematical programming formulations are limited to deterministic, fixed-demand, single-destination, single commodity cases. Optimal control formulations have assumed origin-destination trip rates as continuous functions of time. Variational inequality formulations provide a general formulation platform for several DTA problems such as optimization, fixed point, and complementarity. This formulation provides more realistic traveler behavior than the previous two formulations but still has unresolved problems (Peeta and Ziliaskopoulos 2001). Simulation based models attempt to replicate the complex traffic flow dynamics which is critical for developing meaningful operational strategies for real-time deployment. Simulation models have gained greater acceptance in the context of real-world deployment because of their vis-à-vis realistic traffic modeling. Most existing simulation-based models are also used as part of determining the optimal solution (Peeta and Ziliaskopoulos 2001). Currently, limited research is being performed to address key issues when applying DTA models to real-time deployment and planning. The issues with DTA models have been identified as computational tractability, robustness of the solution methodologies and stability of the associated solutions, fault tolerance and system reliability, operational consistency and model calibration/validation, and demand estimation and prediction (Peeta and Ziliaskopoulos 2001). DTA models have been applied successfully to a transportation network after a natural disaster as shown by Nojimo and Sugito (2000) and Chang (2003).

One research project combined dynamic programming, integer linear programming and Markov chain prediction models (Jiang and Sinha 1998). This research developed an optimization model for bridge maintenance systems that would efficiently optimize the bridge systems and budget allocations. The objective of the model was to obtain optimal budget allocations and corresponding project selections over a time period so that the system effectiveness could be maximized. The output of the model was a list of selected bridges and activities along with the corresponding state and federal costs for each period within the total time period. The model was demonstrated as a comprehensive bridge management system for the Indiana Department of Highways (Jiang and Sinha 1998).

Overview of Single-objective Optimization Models

The model for this research is a constrained, single-objective, optimization model. The goal of optimization models is to find the global optimum answer. By adding constraints to the model, a feasible answer is found within given parameters. Feasibility is defined as a solution that satisfies all the constraints (Zielinski and Laur 2007). When programming a constrained single-objective model, certain criteria are understood to “stop” the trial and error process usually implemented. The three criteria for comparing possible solutions are:

(1) A selection of solutions are feasible but one has a better objective function value,

(2) A selection of solutions are infeasible but one has a lower sum of constraint violations, or

(3) One solution is feasible while the others are infeasible.

When the criteria are met, a single solution or set of solutions to the optimization model is suggested (Zielinski and Laur 2007).

Research has suggested the use of a multi-criteria approach to a constrained single-objective problem proposes the use of an iterative process to replace some of the heuristic nature that is typically found in this type of problem (Dhaenens-Flipo 2001). This research is similar to the current research in that for both models, a time period is given and a total cost is considered. By applying multi-criteria to the problem, a more efficient solution can be found. To obtain the most efficient solution using the multi-criteria approach, the optimum of Pareto is introduced. Optima of Pareto are solutions in which it is impossible to improve one of the criteria without deteriorating another. The optimum of Pareto characterizes a solution x such that in a minimizing multi-criteria environment dealing with n criteria ($C_1 \ldots C_n$) there exists no solution x such that $C_1(x) \leq C_1(x^*), \ldots, C_n(x) \leq C_n(x^*)$, where at least one of the inequalities is strict

(Dhaenens-Flipo 2001). Pareto was a scientist who generalized the algorithm for estimating an “optimum” solution when there is more than one objective function (Coello n.d.). Although typically one solution is desired, by identifying all Pareto-optimal solutions the decision maker is given maximum choices for the final decision. Common features of Pareto-based approaches in literature are: (1) the Pareto-optimal solutions in each generation are assigned either the same fitness or rank and (2) some sharing and niche techniques are applied in the selection procedure (Abbass, Sarker and Newton 2001). A niche represents the location of a maximum point in an optimization problem (Beasley, Bull and Martin 1993). Pareto-optimal solutions are typically found to solve multi-objective problems (MOP) because multiple solutions that satisfy the objective functions are found. Because MOP’s are representative of real-world decision-making, they are the subject of much research. One research article suggests a method for generating the Pareto set of solutions for multiobjective optimization problems by solving a sequence of constrained single-objective problems (Laumanns, Thiele and Zitzler 2006). The solutions of the single-objective problems are often constrained to a single grid cell in a larger grid that is predefined in the objective space. This method is called the epsilon-constraint method and has been used for many years. The optimum solution for each single-objective problem corresponds to a Pareto-optimal solution. The purpose of the Laumanns paper is to present a method of determining the entire Pareto set of solutions based on the epsilon-constraint method but also including other properties such as the distribution of the Pareto-optimal objective vectors. The new method has the advantage of alleviating the necessity to guess a grid size because the constraint values are constantly modified during the run. Another advantage is the applicability when no efficient algorithm is available for solving the constrained single-objective functions. The effectiveness of the method is based on the reduced running time which is measured by the number of calls of a single objective optimizer. This optimizer is bounded by $O(k^{m-1})$, where k is the number of Pareto-optimal objective vectors and m is the number of objectives. This scheme is designed as a generic framework for different single-objective optimizers (Laumanns, Thiele and Zitzler 2006).

A more recent article builds on the concept started by Laumanns, Thiele and Zitzler (2006) by addressing the issue of modifying epsilon to generate at least one solution for every point in the Pareto front (Berube, Gendreau and Potvin 2009). The article focuses on bi-objective constrained optimization problems that have no polynomial time algorithm for solving the single-objective problems, but where the single-objective problems can be solved through branch-and-cut. The method proposes constructing a sequence of epsilon-constraint problems based on a reduction of epsilon by a specifed amount for each sequence. Also, the addition of improvement heuristics are proposed to further optimize the solutions. The first heuristic exploits knowledge of the algorithm by keeping the optimum solutions that are “cut” from the model to be explored at the beginning of each separation phase of the branch-and-cut algorithm. This ensures they are not Pareto-optimal solutions that would be discarded as possible solutions. By only keeping the optimum “cuts”, the running time is reduced for the computations. The other heuristic improvement for the method is to improve the initial feasible solution by exploiting similarities between consecutive solutions to generate a better initial solution with each sequence. A demonstration problem is given in the paper to demonstrate that the epsilon-constraint method can be used efficiently to find the exact Pareto front for BOCO problems with integer objective values. By applying the proposed improvement heuristics, the resolution of the epsilon-constraint problems are solved faster (Berube, Gendreau and Potvin 2009).

Mathematical Modeling Software

The software the mathematical model is written in is GAMS (General Algebraic Modeling System). GAMS is a high-leveling modeling system for mathematical programming and optimization (Rosenthal 2008). It was specifically designed for modeling linear, nonlinear, and mixed integer optimization problems. GAMS allows the user to easily edit programs and converts quickly between linear and nonlinear programming. The program was designed by the GAMS Development Corporation in Washington, D.C. (Corporation, GAMS Development 2008).

Chapter 3

Methodology

Existing recovery phase models deal primarily with the change between post-disaster and pre-disaster travel times and do not focus on prioritizing specific routes for reconstruction. The model developed for this research goes beyond predicting damage to propose a plan for prioritizing the repair and restoration of transportation components (i.e. bridges, tunnels, etc) to restore a highway network and allow accessibility to key businesses in the county. This model differs from other recovery phase models in that specific routes are identified for recovery based on given criteria, such as location of key businesses and routes without size and weight limitations to allow for all types of traffic including passenger cars and freight vehicles. The model is considered to be flexible in that it can be applied to a variety of natural disaster situations or other situations that involve damage to transportation components where decisions on recovery strategies must be made. The model provides flexibility to its user as to the criteria for prioritizing routes for reconstruction. The information needed for the model should be readily available for most state and local agencies who may use the model for pre-planning for disaster events or after an event has occurred and recovery decisions must be made.

The model developed for this research is intended for use by state and local transportation officials as well as planning groups such as metropolitan planning organizations and local emergency management agencies. These groups can use this model as a framework for decision-making in rebuilding highway networks after a disaster. The model is intended to be a first step in the development of a comprehensive modeling framework for prioritization of routes for reconstruction. It is anticipated that results of this research will provide the foundation for extended application and representation of more complex scenarios. This research is limited to the analysis of transportation disruption along highways and neglects the effects of other types of disaster impacts such as damage to homes, business facilities and utility lifelines. The research is also limited to highway networks. Other modes of transportation such as rail and barge are not explicitly considered. By focusing on the transportation lifeline, the other lifelines benefit because of the direct relationship between recovery of the transportation system and total recovery of the affected area.

This chapter is divided into four parts. The first part discusses the general framework for development of the mathematical model. The second part describes data needed for the model and the sources of that data. The third part details the process for implementation of the model and the iterative process the model follows when choosing roadways for priority reconstruction. The fourth part demonstrates the model on the highway system in Shelby County, Tennessee after a hypothetical natural disaster.

Development of the model

In order to determine what factors should be considered in reconstructing highways, state and local officials must decide who will be given priority for highway accessibility. For example, one region may decide to give priority to the job locations of local residents while other areas may choose to provide access to industry or business parks. Each locality is different so the specific community needs must be addressed. For purposes of this research it was decided to give priority to industries in order to facilitate a quick economic recovery. Experience has shown that the effects of disasters on highway components not only disrupt traffic flows, but the economic recovery is also impacted (Werner, et al. 2000). Economic recovery is directly related to how quickly industry can begin manufacturing and shipping its products after a disaster and how quickly people are able to resume work. The speed of the recovery of the transportation network is directly related to the speed of the recovery of the entire disaster stricken area (Chang 2003).

Research has suggested that an effective recovery model should consider, at a minimum, which roadways should be evaluated, the resources available for repairs and the extent of likely damage to these roadways and the transportation components contained within them (Kovel 2000). A list of factors considered in the development of this model is given below:

- Functional classification of roadways considered for reconstruction, such as interstates, arterials and collectors
- Administrative classification of roadways was also considered, such as US highways and state routes
- Types of transportation components in the study area
    - Examples include bridges, overpasses, tunnels

    - Other transportation components such as intersections and uninterrupted segments of roadway were not considered for this research
- Size of the transportation components
    - Examples include the number of spans or length on a bridge or length of a tunnel
- Cost of repair or replacement of the transportation components
- Location of the transportation components
- Possible damage levels to the facilities with varying types of disasters
    - Damage levels are classified as slight damage, moderate damage, extensive damage or complete damage
- Location of major roadways used by priority entities as decided by state and local officials
    - Examples of priority entities could include hospitals, schools, residential areas or businesses
- Location of major businesses
- Shortest paths from businesses to the perimeter of damage of a disaster

After review of current literature, consideration of the recommended factors involved in developing a recovery model and identification of criteria that would be used to assess economic impact, a mathematical formulation for the model was developed. The single objective of the model is to maximize the benefit associated with completing a path. Two of the primary constraints associated with each path that must be met are budget available for repairs and the time to accomplish the repairs. For the purpose of this research, it is assumed that after a disaster all money available for repairs will be spent and that all components of a highway system will eventually be repaired. However, the goal of this model is to spend the money efficiently and in a timely manner so that some benefit is recognized in a shorter time period. The variables used are described below as well as the formulation of the mathematical equations for the model.

To formulate the problem we define the following:

Sets and Indices

i	(1, 2, ….., N) $\in I$	set of paths
j	(1, 2, ….., B) $\in J$	set of bridges
V_i	Set of bridges belonging to path i	

Parameters

t	Time period allowed for repairs
c_j	Cost of repair for bridge
BD	Maximum dollars given for repairs in time period t

B_i Benefit from repairing path *i*

R_j Time for repair of bridge *j*

Variables

x_i 1 if path *i* is completed and zero otherwise

y_j 1 if bridge *j* is repaired and zero otherwise

The formulation to maximize the benefit for each path while minimizing the cost within a given time period and with a specified budget is given by:

$$Max \sum_{i} (B_i x_i) \tag{1}$$

Subject to:

$$\sum_{j \in J} c_j y_j \le BD \tag{2}$$

$$x_i \le y_j \qquad \forall i \in I, j \in V_i \tag{3}$$

$$\sum_{j \in J} R_j y_j \le t \tag{4}$$

$$x_i, y_j \in \{0,1\} \tag{5}$$

The objective function (1) maximizes the benefits from restoring the paths over a period t of financing. Constraints set (2) ensures that the cost of repairing a number of bridges at time period t does not exceed the amount of dollars budgeted for that time period. Constraints set (3) states that the repair of a path will be one if all the bridges on that path have been restored and zero otherwise. Constraints set (4) ensure that the time for repairing the bridges in a path does not exceed the specified time period. Constraint set (5) defines the decision variables.

The model is a single-objective optimization problem. One or more solutions are given that satisfy the objective function without compromising the constraints. For this research, these solutions are the paths that are chosen as a priority for reconstruction. The criteria for the path chosen is maximum benefit within the given constraints.

The output for the model includes the paths that will be completed and bridges that will be repaired while staying within the given budget and time period. It is expected that as budget increases, more paths will be able to be completed. The model is implemented in the General Algebraic Modeling System (GAMS). GAMS is specifically designed for modeling optimization problems (linear, non-linear, mixed integer, etc.), such as the one in this research (Rosenthal 2008). Unfortunately, GAMS is not designed to be used by people with no programming background. In order for local officials to perform this analysis, some programming knowledge will be required. The limitation of not having a user interface is discussed later in the limitations of the model and is also included as a recommendation for future research.

Data Description and Sources

Definition of Benefit Criteria

Each local or state agency must decide the key facilities within the region that need priority access. These entities could be hospitals, schools, businesses, or even residential areas. Identification of benefit criteria must take place first so that paths considered for reconstruction can be defined.

Each path will be assigned a benefit for use in the optimization of the objective functions. This is necessary in order to choose paths for priority reconstruction that may not necessarily be the most cost effective. Examples of benefits could be the fiscal year revenue of businesses, number of beds in a hospital, or the number of houses in a residential area. By assigning a benefit to each path, each path has a type of weighting factor based on its importance to local and regional goals. Benefits should be chosen based on the importance to the region.

Definition of Paths

For this research, major roadways are divided into different paths allowing commodity flows between a specified priority entity and the edge of the perimeter of damage. The perimeter of damage will be based on disaster simulations, historical data or actual inspection after a disaster has hit. A municipality could have any number of paths depending on the number and location of the entities chosen to be a priority in the reconstruction of the highways. There can be a varying number of transportation components along each path. Also, the paths can be different lengths based on the distance from the entity to the edge of the damage perimeter.

Budget

Budget for the reconstruction within a specified time period is input by the user into the model. This budget is determined by the local or state agency that is planning for the reconstruction. For example, the maximum number of dollars given could be the agencies' budget for emergency repairs or an allotment from the federal government if the area is declared a federal emergency location.

Time Period Allowed for Repairs

The time period that is allowed for repairs is also determined by the user of the model. This could be a few months or years depending on the time frame that is desired by the user. One example could be the time period that money is allotted from the federal government if the area is declared a federal emergency location. Once an area has been declared a federal disaster, monies are usually allocated over a 2-year or more period (United States Department of Transportation 2009). For example, if the state department of transportation is receiving $1,000,000 every six months for two years, then the model could be run in six month time periods with a budget of $1,000,000 for each period in order to most efficiently spend each payment from the government.

Transportation Components

The various transportation components contained within a transportation network include the roadway itself, bridges over water, overpasses and also tunnels. These components are important to the repair cost of the paths and the repair time of the paths. The transportation components are classified into 5 levels of damage after a disaster: none, slight, moderate, extensive and complete. These 5 damage levels are defined in the HAZUS-MH software (National Institute of Building Sciences 2008). These damage levels are used for this research to be consistent with the output from HAZUS-MH. The HAZUS-MH software can be used for planning highway reconstruction after disaster as well as the REDARS software (ImageCat, Inc. 2005). For this research, these levels of damage were randomly assigned to the transportation components using the "randbetween" function in an Excel spreadsheet. The "randbetween" function will randomly choose a value within a given range. By varying the level of damage for each bridge, the outcome of a natural disaster is more closely simulated. These damage levels could also be obtained by a visual inspection after an actual disaster. The damage level of each transportation component is the basis for the time of repair of the component and the repair cost of the component.

Repair Cost of the Paths

Along each path, there are a number of different transportation components. The cost of repairs for transportation components is summed over each path. In order to determine the cost of repairs for an individual transportation component, several pieces of information are needed regarding the component. This information includes type of construction for the component, size of the component and level of damage it has suffered or will suffer during a disaster. This information is available from sources such as the Federal Emergency Management Agency (FEMA), Federal Highway Administration (FHWA) and several GIS simulation software packages. For purposes of this research, databases contained in HAZUS-MH and REDARS are used.

The GIS based software HAZUS-MH is used in this research because of its extensive database of information. HAZUS-MH was developed by FEMA. The software contains databases for the on-system bridges that include information on the year built, type of construction, estimated replacement cost, predicted level of damage, description of the bridge, soil liquefaction estimates at bridge location and bridge class. Replacement cost information currently in the HAZUS-MH program is derived from the Applied Technology Council (Applied Technology Council 1985, Council, Applied Technology 1991). According to the HAZUS-MH User's Manual, the information in the ATC reports is to be used only for estimation. It is expected that the user would input replacement costs based on regional and local values pertinent to their transportation components. This is very important especially considering the age of the information. Based on the damage level of a bridge, a repair cost can be estimated as a ratio of the replacement cost. The actual costs for repairs will be based on the bridge type, location, length of the bridge and regional unit costs and local construction practices. Because it is very difficult to estimate these values, research performed in the development of REDARS is used for the repair costs in the current research (Werner, et al. 2000). The mean of the repair cost ratio is given in the table below and is the value used for this research.

Table 3.1 – Replacement Cost Ratio

Damage State	Mean Repair Cost Ratio
None	0.0
Slight	0.03
Moderate	0.08
Extensive	0.25
Complete	1.0

REDARS bases the values in this table on the equation:

$$RCR_T = \sum_{i=2}^{S} RCR_i \bullet P\left[D = ds_i(S_a)\right] \leq 1.0$$

Where RCR_T is the portion of the total replacement cost for the bridge, $P\left[D = ds_i(S_a)\right]$ is the probability of being in damage state ds_i for spectral acceleration S_a , and RCR_i is the replacement cost for the bridge (Mander and Basoz 1999).

For this research, the cost of repairs for each transportation component is based on the replacement cost of the component from HAZUS-MH multiplied by the ratio of the replacement cost based on the level of damage given in REDARS.

Repair Time for Each Path

The sum of the time to repair each transportation component within a path is the time of repair for that path. Time required to repair the transportation components is another aspect of this research that is difficult to estimate. It is very reliant on the damage to the bridge, accessibility to the bridge and accessibility to resources to perform the needed repairs. A database for the REDARS software gives estimated times for repairs based on the various bridge damage levels (Werner, et al. 2000). The estimates are based on the size of the bridge (length, width, number of spans). The ranges used for the REDARS software is given in Table 3.2.

Table 3.2 – Time Periods for Repair to Bridges

Damage State	Duration
None	None*
Slight	2-3 weeks
Moderate	2-4 weeks
Extensive	4-12 weeks
Complete	3-10 months

These ranges are used for repair times in the current research with one exception. The only exception is that bridges with no damage are assessed a repair time of 1 to 5 days to allow for inspection of the bridge to assure there is no damage and that the bridge is safe for traffic. The time for repair of each transportation component is randomly generated within an Excel spreadsheet using the “randbetween” function previously discussed.

Implementing the model

The model can be implemented based on one of two possible scenarios. The first is a planning application using a hypothetical disaster with output from some GIS based software such as HAZUS or REDARS (ImageCat, Inc. 2005, National Institute of Building Sciences 2008). These two software packages estimate damage to transportation facilities based on the disaster scenario input by the user. The second scenario is based on post-disaster damage assessments. A visual inspection by a trained professional could determine the damage level to the bridge after an event has occurred. Since this model deals with the recovery phase, it is assumed that some clean-up and debris removal has already occurred as part of the evacuation and emergency response phase.

The flow chart below shows the basic steps for implementing the model based on the two scenarios: planning or post-disaster.

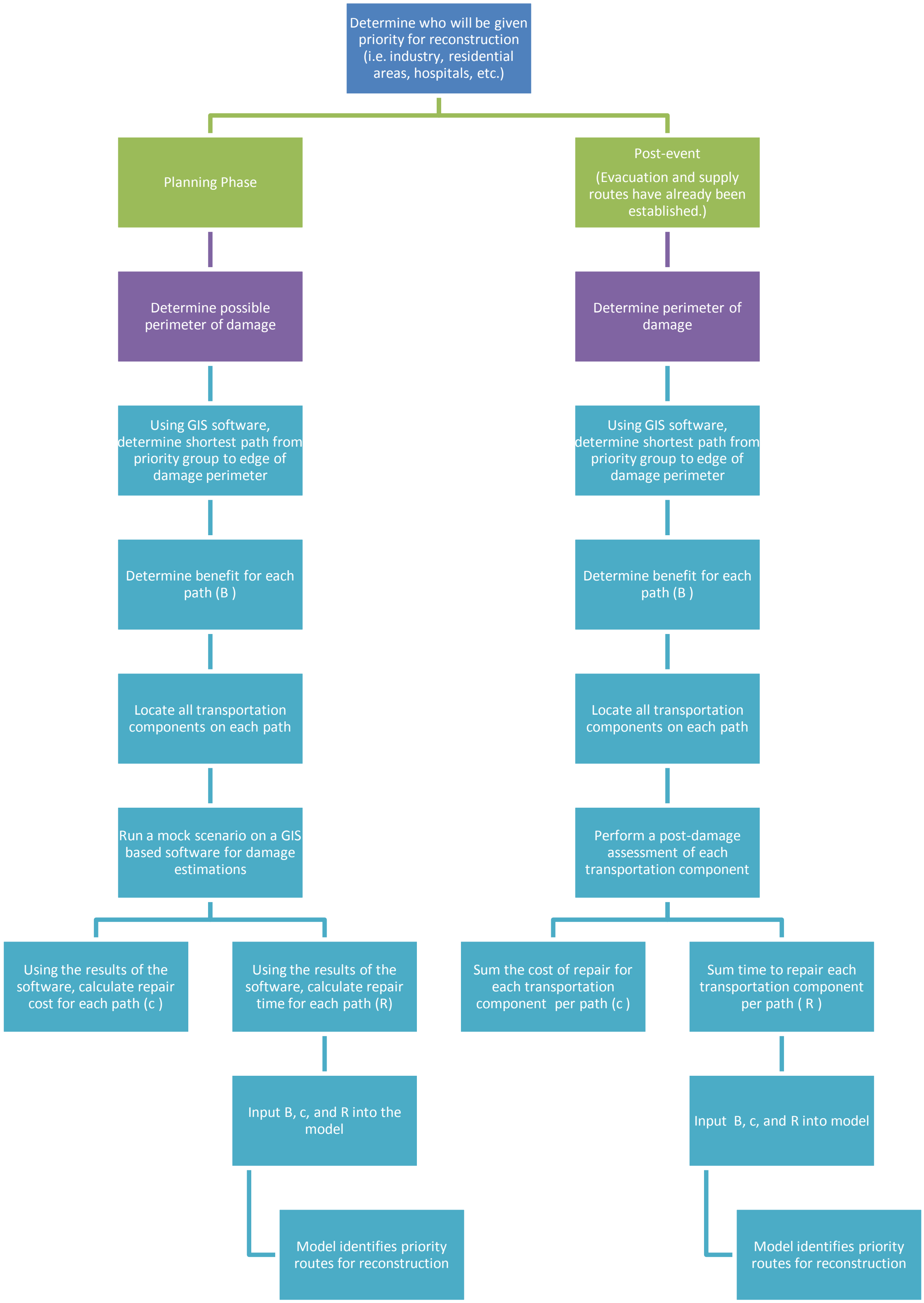

Figure 3.1 – Steps for Implementing the Model

Iterative Process of the Model

The model uses an iterative process to determine the paths for reconstruction. Once all the inputs have been entered, equation (1) is calculated for the first bridge. If the answer given by the equation does not exceed the constraint given in equation (3), the next constraint set is checked. If the solution to equation (1) meets all the requirements given in the constraints, the bridge is assigned a decision variable of “1”, meaning it is recommended for reconstruction. After that, the next bridge is run through the process until all bridges have been assigned either a “1” or a “0” (not reconstructed). Then each path is checked to make sure all the bridges within that path have been recommended for reconstruction. In other words, all bridges within a path have been assigned a “1”. If this is true, the path is assigned a “1”. Otherwise the path is assigned a “0”. The next step is calculating the repair time for each path recommended for completion. If the path repair time is less than the time period allowed by the user, the objective function is then calculated for that path. The path with the optimum objective function is chosen as the first path to be reconstructed. The second most optimum objective function is chosen as the second path and so on.

Figures 3.2 and 3.3 demonstrate the iterative process the model uses to determine which paths should be reconstructed first. Figure 3.2 shows how bridges are assigned a “1” for recommended reconstruction or a “0”, not recommended for reconstruction.

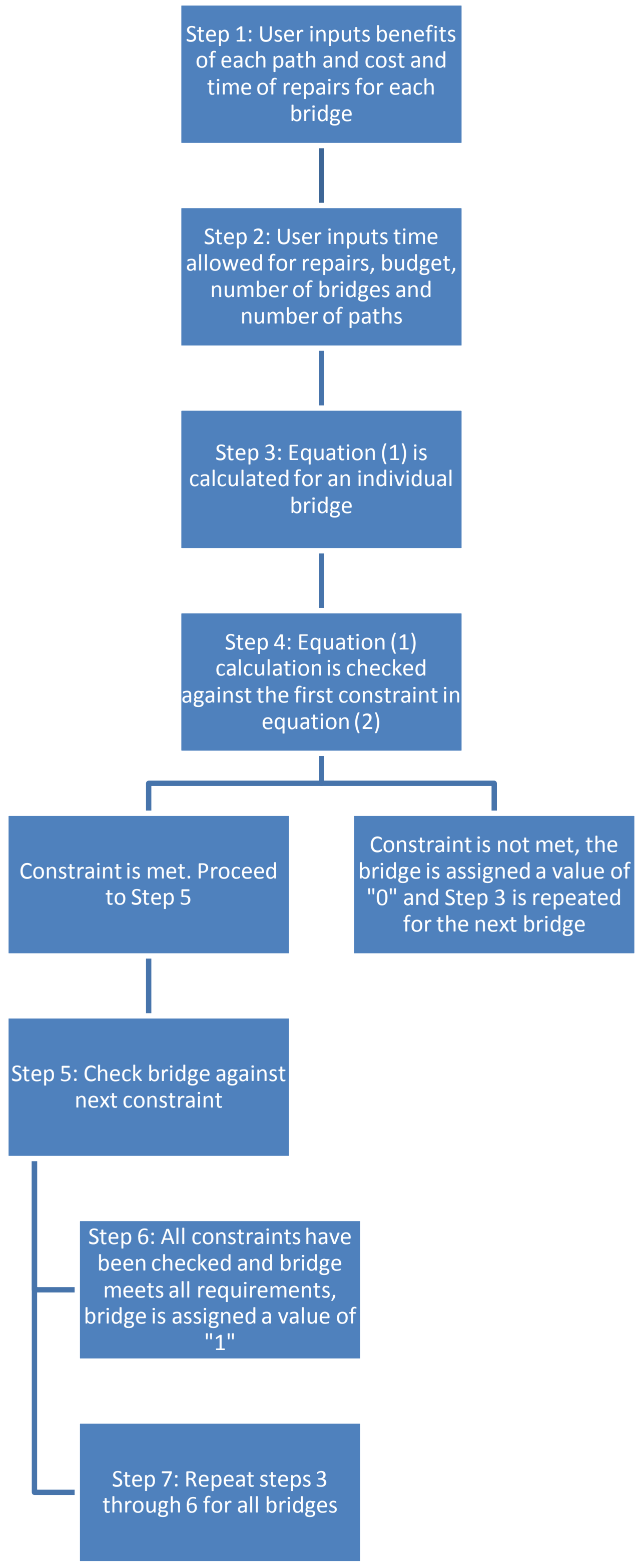

Figure 3.2 – Steps for Determining Bridges for Reconstruction

Once all bridges have been assigned either a “1” or a “0”, each path will be processed to see which one will be recommended for priority reconstruction. Figure 3.3 demonstrates the process for recommendation of paths.

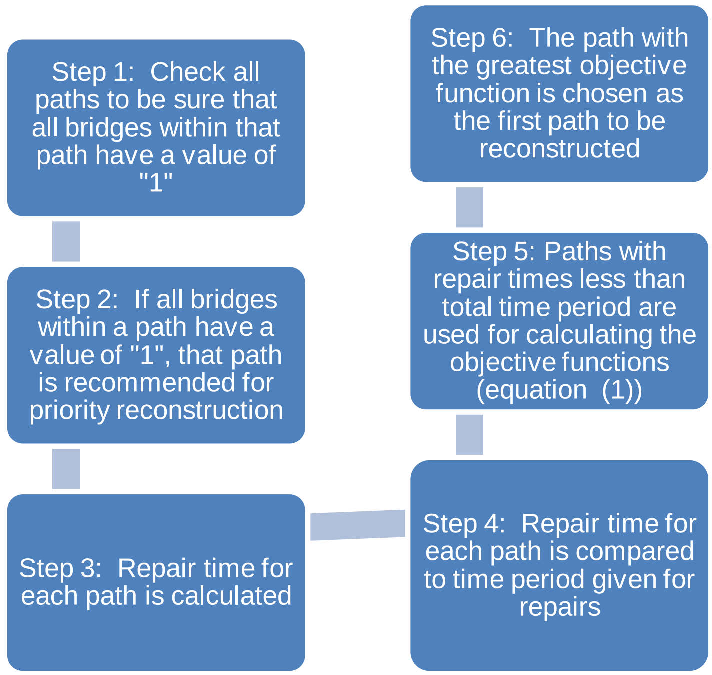

Figure 3.3 – Steps for Prioritizing Paths

Demonstration of Model in Shelby County, Tennessee

To demonstrate the use of the model it was applied to a highway network in Shelby County, Tennessee. The demonstration follows the planning phase illustrated in Figure 3.1 since an actual, measurable event has not occurred in Shelby County in almost 200 years. At the heart of Shelby County is the metropolitan Memphis area, including the city of Memphis. Shelby County is home to five class one railroads, the largest cargo airport in the country and over

100 warehouses for major retailers such as Nike, DVD distributors and others. Over 150 metropolitan markets can be reached by truck overnight from Shelby County. If a significant event were to occur that crippled the transportation system, the economic effects would be far reaching. For these reasons, the top 25 revenue producing industries were chosen as the priority entities for this research. The benefit associated with each industry is its fiscal year revenue for 2007 (Bolton, Emphasis: Top 50 Public Companies 2008). This was chosen because of the importance of industry to the economic vitality of the Shelby County area. This research identifies a restoration strategy to allow highway access to major businesses within given time period and budget. A list of these businesses is located in Appendix A. Figure 3.4 shows the location of Shelby County highways used for the current research. Only US highways and interstates were considered because they are the primary freight routes within Shelby County.

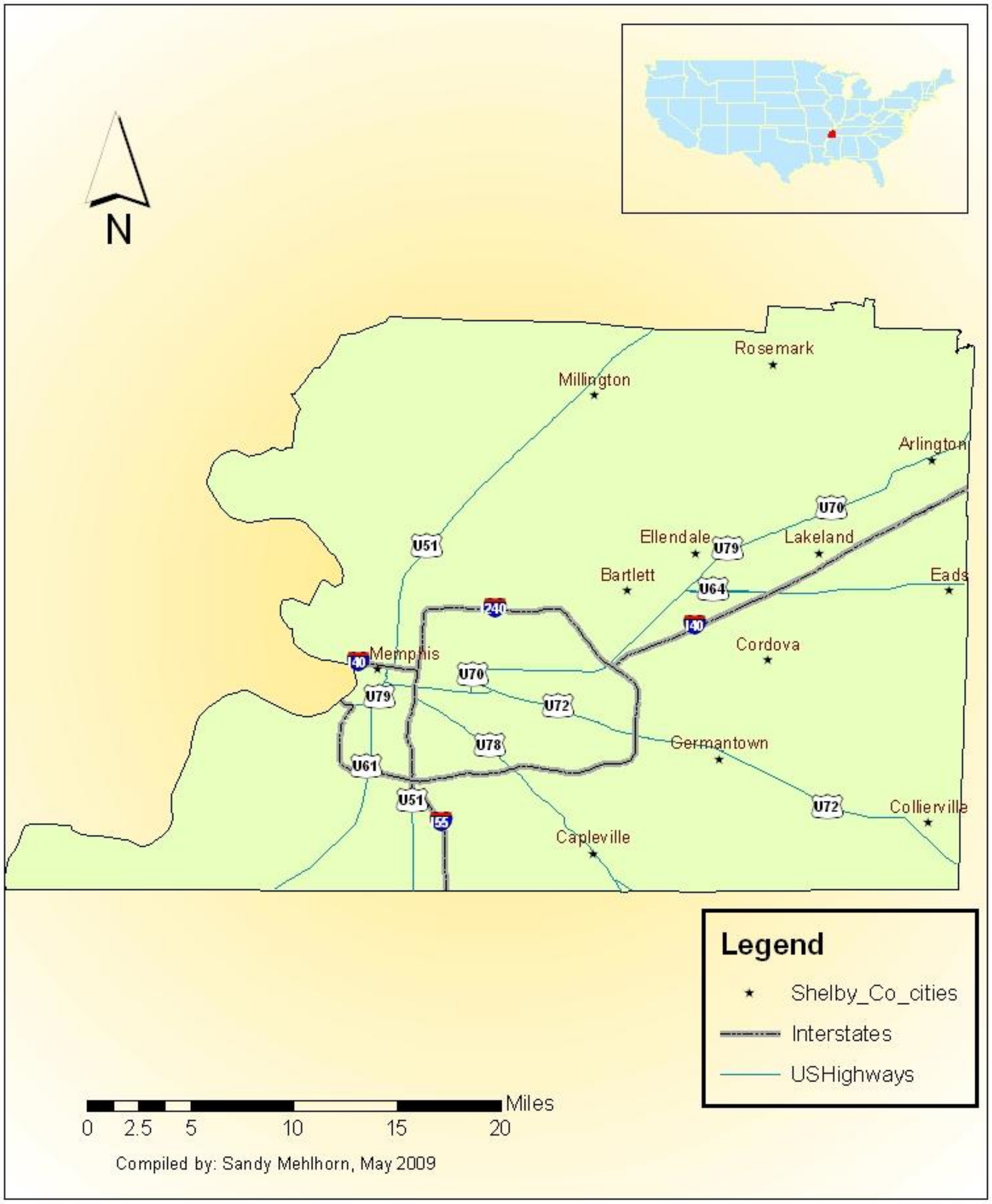

Figure 3.4 – Map of Shelby County US Highways and Interstates

Another reason for choosing Shelby County to demonstrate the model is its location in the New Madrid Seismic Zone (NMSZ). The NMSZ is considered the most hazardous seismic zone in the central and eastern United States by engineers, seismologists, and public officials (Hwang, Jernigan and Lin 2000). The largest earthquake in history took place in the NMSZ in the winter of 1811-1812 near Shelby County and scientists consider this area to be capable of another catastrophic earthquake at any time (Rose, et al. 1997). The NMSZ is considered by the USGS as the most active earthquake region over any other region in the United States east of the Rocky Mountains (Schweig, Gomberg and Hendley II 1995).

Of the various structural transportation components, the Memphis metropolitan area is limited to bridges. There are no tunnels on the selected highway network in Shelby County. However, these bridges include structures over water and overpasses. There are 218 bridges evaluated for the current research. The bridges are located on interstates and US highways in Shelby County. Memphis has two bridges that cross the Mississippi area in the downtown area. These bridges are assumed impassable for purposes of this research. Previous research performed on bridges in Shelby County after a hypothetical 7.0 magnitude earthquake have shown 35% are expected to sustain significant damage, 30% will sustain repairable damage and another 35% will sustain minor or no damage. (Hwang, Jernigan and Lin 2000) The Arkansas Center for Earthquake Education and Technology Transfer at the University of Arkansas at Little Rock predicts that an earthquake of magnitude 7.0-7.9 will result in 30% of bridges collapsed (1998).

For this research, routes were created based on the shortest path from the business to the edge of the county. ArcGIS® was used to identify the shortest route along the designated highways from each industry to the edge of the county. This is done by creating a network in the Network Dataset toolbox from a file that contains information about the highway system such as miles, speed, number of lanes, etc. This network is then loaded into Network Analyst Tools. Within Network Analyst, routes can be created based on various criteria. This is referred to as the Closest Facility routing and is based on miles. These routes become paths within the model. It is assumed that once the freight reaches the edge of the county, it is outside the damage perimeter and can travel on any roadway in any direction necessary. The edge of the county is used for this demonstration as the edge of the damage perimeter. This is only an estimate until an actual damage simulation can be performed. Another way of estimating the damage perimeter is by historical data from an actual event. Figure 3.5 shows the nine paths that were chosen for this research in relation to the location of the businesses.

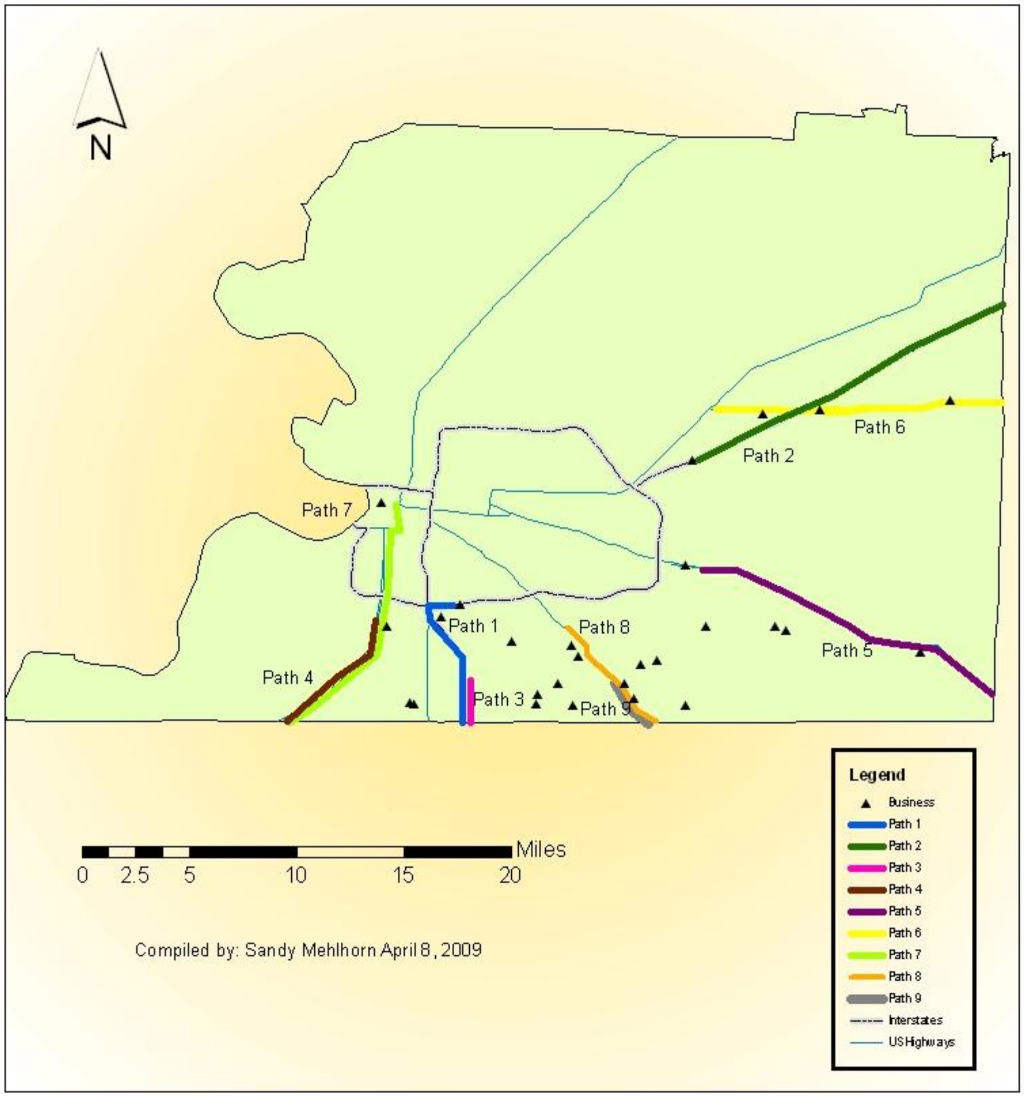

Figure 3.5 – Map of Paths and Business Locations for Shelby County

It is important to note that many of the businesses are not located directly on the highways shown. The connecting roads between the businesses and the major roadways were used in the ArcGIS Network Analyst to find the shortest path to the edge of the county, but they are assumed to be passable for this phase of the process. It was also assumed that the two bridges crossing the river are inaccessible due to damage from the disaster. Therefore, business located in the downtown area of Memphis cannot cross the river as part of the shortest path out of the county. A table showing the paths and their corresponding roadway is given below.

Table 3.3 – Path Number and Corresponding Roadway Name

Path Number	**Roadway**
1	Interstates 240 & 55
2	Interstate 40
3	Interstate 55
4	US 61
5	US 72
6	US 64
7	US 61
8	US 78
9	US 78

A cost for repairing each path is identified as the sum of the cost of repairing all the transportation components on the path. This information is given based on the level of bridge damage and cost to replace the bridge. Bridge damage levels are defined as none, slight, moderate, extensive and complete in accordance with output from FEMA's HAZUS software. For this research, the bridge damage levels and time for repair are randomly generated as described previously. For each damage level, the ratio of the replacement cost is used as the repair cost based on Table 3.1 as contained in the REDARS software. The ranges for the repair times are the same as the values in Table 3.2 except for bridges with no damage, which are assessed a repair time of 1 to 5 days to allow for proper inspection of the bridge. For this demonstration, the benefit selected is the sum of the fiscal year revenue for each industry using the path. In Shelby County, many of the paths contain multiple industries. This allows a weighting factor for the path based on the importance to the regional economy each industry contributes.

A summary of the data used for the Shelby County demonstration and the sources of the data are given in the following table.

Table 3.4 – Shelby County Input Data Descriptions

Input	Data Description	Source
Priority Entity	Top 25 businesses based on 2007 revenues	Memphis Business Journal
Paths	Shortest path(business to edge of county)	ArcGIS
Transp. Components	218 bridges	HAZUS-MH database
Budget	Varying amounts	Assumed value
Repair Time of Bridges	6 month periods for 5 years	Assumed value
Repair Cost of Bridges	Ratio of replacement cost	Ratio: REDARS Replacement cost: HAZUS-MH
Repair Time of Bridges	Varying times	REDARS
Path Benefit	2007 Fiscal year revenue	Memphis Business Journal

Once all parameters are input in the model, the model is implemented. The results from the implementation of the model for Shelby County are given in the Results and Discussion chapter.

Chapter 4

Results and Discussion

The purpose of this research is to provide a method for prioritizing routes in a highway network for reconstruction after a natural disaster. The model constructed for this research provides transportation agencies and planners a framework for decision-making. To demonstrate the application of the model, the highway network for Shelby County, Tennessee is used. This exercise demonstrates the implementation of the model used for the planning phase as outlined in the flow chart for implementing the model as shown in Figure 3.1 in the Methodology chapter of this document. Before the demonstration, the validation of the model is presented.

Validation of the model

The current research involves the development of a single-objective optimization model with multiple constraints. These types of models are usually not subjected to a validation process as simulation models are. However, techniques used for verification and validation of simulation models can be applied to this research. Verification and validation techniques provide a system of checks and balances to help ensure there are no errors in the model development. The model for this research has been verified and validated through several of these methods. The purpose of the validation exercise is to ensure errors are being corrected during each step of the development and to test the sensitivity of the model to various parameters.

The process of modeling has several steps involved. The simplified version of these steps is: (1) identification of the problem, (2) development of the conceptual model for the problem, and (3) translation to the computerized model. Each step of the modeling process has techniques for validating the model. Verification and validation at each step in the modeling phase helps to detect problems before the finished product. The definition of model validation is usually "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Sargent 1998). There are three approaches to determining the validity of a model. The most common approach is for the development team to make the decision as to the validity of the model. This is sometimes referred to as expert intuition (Hillston 2003). Another approach is using a third party to decide whether or not the model is valid. This method can be extremely costly and time consuming. The last approach to model validation is called scoring. Scores or weights are subjectively assigned to the performance of various phases of the model and then the scores are summed to provide an overall performance measure. This method is very subjective in determining the scores or weights and the determination of a passing score. It is possible for the model to have a passing score although there are problems and deficiencies (Sargent 1998). For these reasons, this method is generally not used.

There are many techniques used for verifying and validating models. Usually a combination of techniques is used to ensure quality control. Some of the techniques used for verification and validation of the current research are: (1) predictive validation, (2) simplified models, (3) continuity testing, (4) degeneracy testing, and (5) consistency testing.

Predictive validation is using the model to predict behavior. Comparisons are then made between the system's behavior and the models' prediction. System data may come from an operational system or experiments performed on the system. To perform these experiments, simplified models are used to minimize the output to be checked. The theory behind this method is that if a model will not work for simple cases, it will not work for complex cases. However, just because a model works in simple cases does not mean no errors will be incurred in a complex case (Sargent 1998). Continuity testing consists of running the model several times with slightly different values for input parameters. In general, a slightly different change in an input parameter should produce a slightly different change in the output. Any large or unusual changes in output could indicate an error in the model. Degeneracy testing consists of checking the use of the model for extreme cases of input parameters. Extreme cases do not represent typical cases but they can be used to detect errors in the model that may not otherwise be detected. Consistency checking consists of changing the workload within a system to see if similar characteristics in the output are observed. It is assumed that similarly loaded systems will exhibit similar characteristics (Hillston 2003). For this research, the number of paths and bridges within the network can be varied and results compared at various budget levels and time periods.

As previously mentioned, each step of the modeling process can be verified and validated to ensure accuracy throughout the development of the model. Next, each step in the process will be discussed and the various methods of verification and validation used will be explained. First is the identification of the problem. The primary focus here is on data validity. Having valid data ensures that the outputs are relatively accurate. Because the current research has been developed based on some future hypothetical disaster occurrence, data must be randomly generated to perform testing of the model. However, it is important to assume that the inputs are reasonable for the scenario. The bridge information such as repair costs, time of repairs and locations of the bridges should be obtained from dependable sources such as the Federal Highway Administration and the Federal Emergency Management Agency, as was the data for this research. Other sources of this data could include state and local departments of transportation.

The second step in the modeling process is the conceptual model. Validation in this phase is used to determine if the theories and assumptions underlying the conceptual model are correct and that the model representation of the problem is reasonable for the intended purpose of the model. The primary validation methods for this phase are face validation and tracing. Face validation involves the set of model equations being evaluated to determine correctness and reasonableness for the models' purpose. Tracing tracks entities within each submodel to determine if the overall model is correct. By building very small and simple models with single objectives, errors could be corrected early in the development process. All these simple models were combined to obtain the final single-objective optimization model. This is the process of validation referred to as simple models. It checks the operational validity of the conceptual model. The operational validity is concerned with determining that the model's output behavior is accurate for the model's intended purpose. This is where most of the model's validation takes place. Predictive validation is the primary validation method for this. The model is used to predict the system behavior and then comparisons are made between the system behavior and the model output. This research would be classified as a non-observable system meaning there are no actual data from a real system to compare the output of the model (Sargent 1998).   No data has been collected after a natural disaster concerning which roadways were repaired first and at what cost and time. For this reason, the predictive validation comes from multiple outputs from the model with varying parameters. To obtain a high level of confidence in a model and its results, at least two different sets of experimental conditions is required (Sargent 1998). The verification method for this type of validation is continuity testing, degeneracy testing, and consistency testing. These methods basically test the sensitivity of the model to the various parameters.

Continuity Testing

Continuity testing is performed by running the model several different times with slightly different values of input parameters. Changes in output are compared to make sure slight changes in the input lead to slight changes in the output. For this test, a hypothetical highway network with 20 paths and 5 bridges per path is used within the model. Within an Excel spreadsheet, bridge damage levels for each bridge were randomly generated. Based on the bridge damage level, random repair costs and repair times were randomly generated within a given range of values. The final input, path benefit, was randomly assigned to each path for the purposes of this exercise. These values are only hypothetical and have no correlation to an actual network. They are only used for the purpose of validating the continuity of the model. Figure 4.1 shows what the hypothetical network and location of paths and bridges could look like.

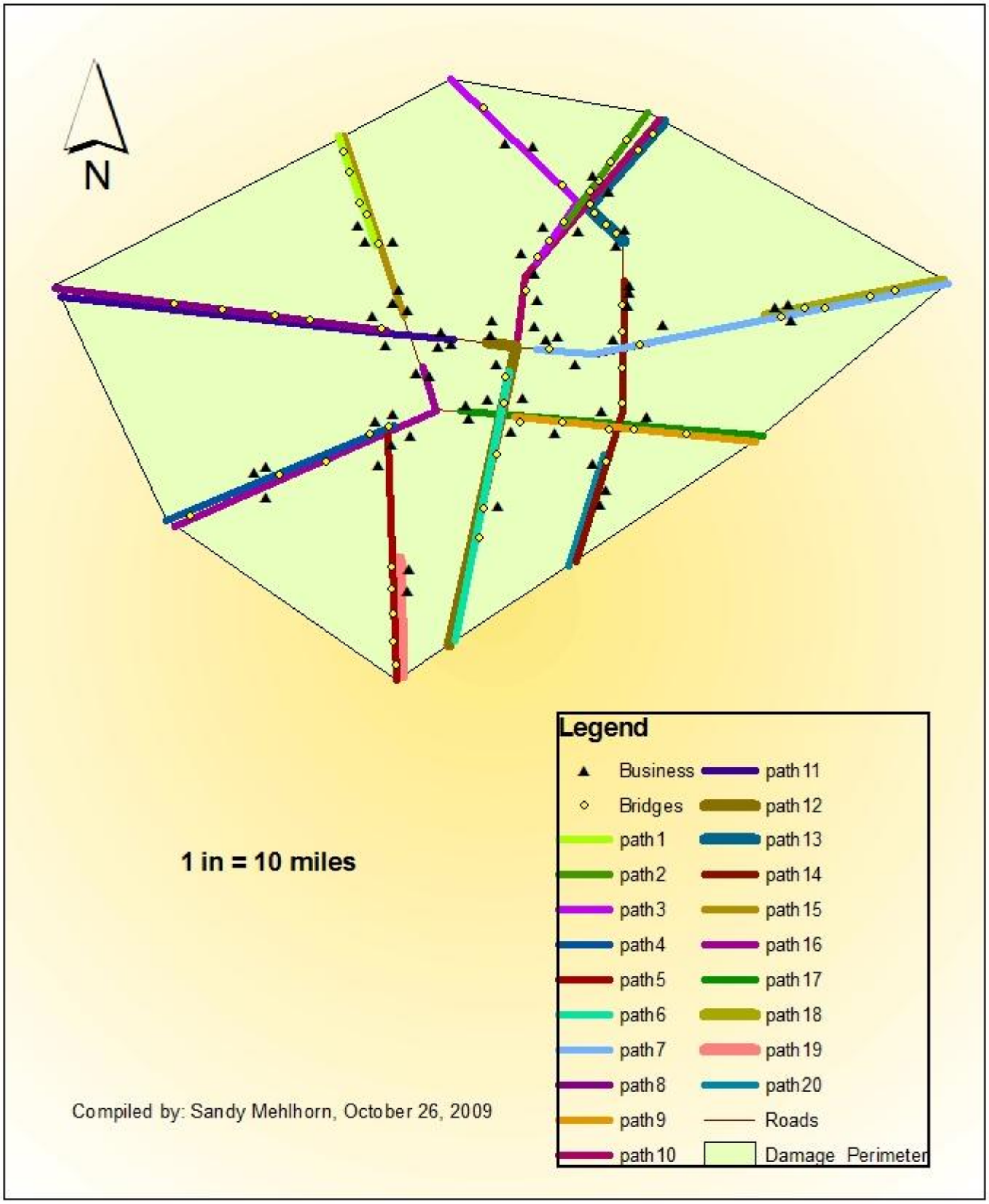

Figure 4.1-Example of Hypothetical Network with 20 Paths and 100 Bridges

A summary of the path characteristics is given in Table 4.1. In this table the first column denotes the path number, the second column gives the bridge number of bridges within each path, the third column denotes the total replacement cost of each bridge, the fourth column denotes the damage level of the bridge, the fifth column denotes the cost to repair the bridge, which is a fraction of the replacement cost based on the damage level of the bridge, the sixth column denotes the repair time in days to repair the bridge, the seventh column represents the total cost to repair the path and the eighth column is the benefit realized once the path is completed. As mentioned previously, simplified models are used for the validation testing so the numbers in the table are much less than actual values would be. These numbers are randomly generated by an Excel spreadsheet solely for the purpose of testing the model. The benefit is assigned in dollars for this testing although depending on the benefit assigned to a path it could be number of hospital beds, or possibly number of commuters that would benefit from completion of the path.

Table 4.1 - Characteristics of Hypothetical 20 path-100 Bridge Network

Path No	Bridge No	Replace Cost	Damage Level	Bridge Repair Cost ($)	Repair Time (days)	Total Cost of Path ($)	Benefit ($)
1	1	$1,107.69	slight	277	30		
	2	$2,029.34	complete	2029	120		
	3	$930.20	moderate	465	60		
	4	$3,261.06	None	500	10		
	5	$2,611.41	complete	2611	120	5383	100
2	6	$2,702.51	slight	676	30		
	7	$4,105.87	None	500	10		
	8	$1,707.58	moderate	854	60		
	9	$754.43	None	500	10		
	10	$2,951.85	None	500	10	1529	200
3	11	$2,095.63	slight	524	30		
	12	$648.65	slight	162	30		
	13	$3,795.23	complete	3795	120		
	14	$2,619.54	None	500	10		
	15	$1,852.14	slight	463	30	4944	300
4	16	$1,481.91	moderate	741	60		
	17	$2,101.33	moderate	1051	60		
	18	$2,792.47	complete	2792	120		
	19	$1,596.67	complete	1597	120		
	20	$1,227.44	slight	307	30	6488	400
5	21	$1,766.32	None	500	10		
	22	$2,316.60	slight	579	30		
	23	$3,600.21	slight	900	30		
	24	$1,304.42	moderate	652	60		
	25	$492.97	extensive	370	90	2501	500
6	26	$2,119.58	extensive	1590	90		
	27	$1,122.66	moderate	561	60		
	28	$1,368.58	moderate	684	60		
	29	$3,155.42	None	500	10		
	30	$1,240.84	complete	1241	120	4076	600
7	31	$1,847.29	slight	462	30		
	32	$958.86	slight	240	30		
	33	$1,204.63	moderate	602	60		
	34	$1,547.92	slight	387	30		
	35	$364.24	moderate	182	60	1873	700

Table 4.1 - Characteristics of Hypothetical 20 path-100 bridge Network

Path No	Bridge No	Replace Cost	Damage Level	Bridge Repair Cost ($)	Repair Time (days)	Total Cost of Path ($)	Benefit ($)
8	36	$111,110.69	slight	27778	30		
	37	$894.14	complete	894	120		
	38	$3,947.49	complete	3947	120		
	39	$2,408.69	moderate	1204	60		
	40	$2,408.69	moderate	1204	60	35028	800
9	41	$1,212.47	None	500	10		
	42	$1,212.47	moderate	606	60		
	43	$1,005.90	extensive	754	90		
	44	$1,925.99	None	500	10		
	45	$2,720.76	None	500	10	1361	900
10	46	$1,780.86	slight	445	30		
	47	$2,226.07	complete	2226	120		
	48	$1,335.64	slight	334	30		
	49	$8,119.08	slight	2030	30		
	50	$7,378.05	extensive	5534	90	10569	1000
11	51	$1,604.66	extensive	1203	90		
	52	$1,965.33	moderate	983	60		
	53	$1,184.25	moderate	592	60		
	54	$1,184.25	None	500	10		
	55	$1,347.19	None	500	10	2778	1000
12	56	$1,347.19	complete	1347	120		
	57	$1,548.63	complete	1549	120		
	58	$1,548.63	None	500	10		
	59	$7,378.05	slight	1845	30		
	60	$6,170.14	slight	1543	30	6283	900
13	61	$3,944.78	None	500	10		
	62	$3,616.03	None	500	10		
	63	$5,161.53	moderate	2581	60		
	64	$2,460.73	None	500	10		
	65	$1,461.38	None	500	10	2581	800
14	66	$1,576.00	extensive	1182	90		
	67	$991.65	None	500	10		
	68	$1,149.89	None	500	10		
	69	$22,070.85	complete	22071	120		
	70	$4,148.50	moderate	2074	60	25327	700

Table 4.1 - Characteristics of Hypothetical 20 path-100 bridge Network

Path No	Bridge No	Replace Cost	Damage Level	Bridge Repair Cost ($)	Repair Time (days)	Total Cost of Path ($)	Benefit ($)
15	71	$1,877.52	extensive	1408	90		
	72	$4,663.42	None	500	10		
	73	$2,628.52	complete	2629	120		
	74	$6,241.28	moderate	3121	60		
	75	$775.53	moderate	388	60	7545	600
16	76	$775.53	moderate	388	60		
	77	$814.30	moderate	407	60		
	78	$1,335.22	None	500	10		
	79	$2,359.94	extensive	1770	90		
	80	$1,184.39	slight	296	30	2861	500
17	81	$581.64	None	500	10		
	82	$581.64	extensive	436	90		
	83	$772.82	complete	773	120		
	84	$772.82	moderate	386	60		
	85	$730.33	extensive	548	90	2143	400
18	86	$730.33	slight	183	30		
	87	$1,553.90	moderate	777	60		
	88	$1,600.52	extensive	1200	90		
	89	$2,085.08	complete	2085	120		
	90	$5,227.11	complete	5227	120	9472	300
19	91	$5,065.44	extensive	3799	90		
	92	$772.82	complete	773	120		
	93	$1,781.43	slight	445	30		
	94	$1,429.88	complete	1430	120		
	95	$640.81	moderate	320	60	6768	200
20	96	$738.03	complete	738	120		
	97	$3,286.72	None	500	10		
	98	$3,286.72	extensive	2465	90		
	99	$1,801.39	None	500	10		
	100	$1,017.88	moderate	509	60	3712	100

Table 4.1 will be used for running 4 tests of the model, increasing the repair costs at each run. It is expected that as costs increase, the number of paths

completed will be reduced or paths with lower costs will be chosen over paths with a higher benefit. This trial is directly related to the budget constraint since the total cost of repairing paths cannot exceed the budget. Results from the first run, using the input data from Table 4.1, are given below in Table 4.2. In Table 4.2, the first column shows the time period being allowed for repairs, the second column shows the paths that can be completed within the given time period and the third column shows the benefit that is recognized by completing the paths.

Table 4.2 - Model Output for Continuity Test 1-Budget: $1,000,000

Time	Paths completed	Recognized Benefit ($)
6 months (180 days)	9	900
1 year (365 days)	2,7	900
1.5 years (545 days)	2,7,9	1800
2 years (730 days)	2,5,7,9	2300
2.5 years (910 days)	2,5,7,9,13	3100
3 years (1095 days)	2,5,7,9,11,13	4100
3.5 years (1275 days)	2,5,7,9,11,16	3800
4 years (1460 days)	2,5,7,9,11,13,17	4500
4.5 years (1640 days)	2,5,7,9,11,13,16,20	4700
5 years (1825 days)	2,3,5,7,9,11,13,16,20	5000

The benefit for each time period fluctuates until it reaches its greatest point at the final 5 year time period. This is due to the fact that the model is being forced to find the maximum number of paths it can complete within the given time period and given budget. For continuity test 2, budget and time will remain constant but costs will be increased by 5%. Table 4.3 shows the results of test 2 using the same format as Table 4.2.

Table 4.3 - Model Output for Continuity Test 2-Budget: $1,000,000

Time	Paths completed	Recognized Benefit ($)
6 months (180 days)	9	900
1 year (365 days)	2,7	900
1.5 years (545 days)	2,7,9	1800
2 years (730 days)	2,5,7,9	2300
2.5 years (910 days)	2,5,7,9,13	3100
3 years (1095 days)	2,5,7,9,11,13	4100
3.5 years (1275 days)	2,5,7,9,11,16	3800
4 years (1460 days)	2,5,7,9,11,13,17	4500
4.5 years (1640 days)	2,5,7,9,11,13,16,20	4700
5 years (1825 days)	2,3,5,7,9,11,13,16,20	5000

No changes in the paths completed or the number of bridges completed were noted when costs were increased by 5%. For continuity test 3, costs will be increased an additional 5%. Table 4.4 shows results from test 3 in the same format as Table 4.2.

Table 4.4 - Model Output for Continuity Test 3-Budget: $1,000,000

Time	**Paths completed**	**Recognized Benefit ($)**
6 months (180 days)	9	900
1 year (365 days)	2,7	900
1.5 years (545 days)	2,7,9	1800
2 years (730 days)	2,5,7,9	2300
2.5 years (910 days)	2,5,7,9,13	3100
3 years (1095 days)	2,5,7,9,11,13	4100
3.5 years (1275 days)	2,5,7,9,11,16	3800
4 years (1460 days)	2,5,7,9,11,13,17	4500
4.5 years (1640 days)	2,5,7,9,11,13,16,20	4700
5 years (1825 days)	2,3,5,7,9,11,13,16,20	5000

Again there is no change in the number of paths completed and the number of bridges completed. For continuity test 4, repair costs are increased an additional 10%. Table 4.5 shows the results from test 4 in the same format as Table 4.2.

Table 4.5 - Model Output for Continuity Test 4-Budget: $1,000,000

Time	**Paths completed**	**Recognized Benefit ($)**
6 months (180 days)	9	900
1 year (365 days)	2,7	900
1.5 years (545 days)	2,7,9	1800
2 years (730 days)	2,5,7,9	2300
2.5 years (910 days)	2,5,7,9,13	3100
3 years (1095 days)*	2,5,7,9,13,16	3600
3.5 years (1275 days)	2,5,7,9,11,16	3800
4 years (1460 days)*	2,5,7,9,13,16,17	4000
4.5 years (1640 days)	2,5,7,9,11,13,16,20	4700
5 years (1825 days)*	2,3,5,7,9,11,16,20	4200

For this run of the model, at 3 and 4 years, path 16 was chosen to be constructed instead of path 11. However, 6 paths and 30 bridges were still completed at year 3 and 7 paths and 35 bridges were completed at year 4. Path 11 has a much larger benefit than path 16 and a less cost so it is interesting that the model chose to prioritize path 11 higher than path 16. Given more time, the model chooses to complete both path 11 and 16. Because a fewer number of paths can be completed due to the increased repair costs, the total recognized benefit is also less for this output.

A total increase of 20% was added to the cost from Test 1 to Test 4. The model completed the same number of paths and the same number of bridges for every test. It can be concluded from this that the model is not very sensitive to the repair cost parameter.

The same continuity tests were performed on the model with varying time for repairs. The path information used for the testing is given in Table 4.6 which presents similar information with Table 4.1. The primary difference is in the fourth column where repair time has been increased by 5%.

Table 4.6 - Continuity Test –Repair Time

Path Number	No. of bridges	Total repair cost ($)	Total repair time (days)	Path Benefit ($)
1	5	5383	357	100
2	5	1529	126	200
3	5	4944	231	300
4	5	6488	410	400
5	5	2501	231	500
6	5	4076	357	600
7	5	1873	221	700
8	5	35028	410	800
9	5	1361	189	900
10	5	10569	315	1000
11	5	2778	242	1000
12	5	6283	326	900
13	5	2581	105	800
14	5	25327	305	700
15	5	7545	357	600
16	5	2861	263	500
17	5	2143	389	400
18	5	9472	441	300
19	5	6768	441	200
20	5	3712	305	100

Results for this test are shown in Table 4.7 where the first column denotes the time allowed for the repairs, the second column denotes the paths completed within the given time period, and the third column is the benefit that is recognized when the paths are completed.

Table 4.7 - Model Output for Continuity Test 5-Budget: $1,000,000

Time	Paths completed	Recognized Benefit ($)
6 months (180 days)	2	200
1 year (365 days)	2,7	900
1.5 years (545 days)	2,7,9	1800
2 years (730 days)	2,7,9,13	2600
2.5 years (910 days)	2,5,7,9,13	3100
3 years (1095 days)	2,5,7,9,11	3300
3.5 years (1275 days)	2,5,7,9,11,16	3800
4 years (1460 days)	2,5,7,9,11,13,16	4600
4.5 years (1640 days)	2,3,5,7,9,11,13,16	4900
5 years (1825 days)	2,5,7,9,11,13,16,17	5000

The repair time for each bridge will be increased 5% for the next test to see how the model behaves. For this continuity test, the benefit steadily increases with each time period versus the previous outputs that showed fluctuating benefits.

Table 4.8 shows the results of test 6 with increased repair times. The table is in the same format as Table 4.7.

Table 4.8 - Model Output for Continuity Test 6-Budget: $1,000,000

Time	Paths completed	Recognized Benefit ($)
6 months (180 days)	2	200
1 year (365 days)	2,7	900
1.5 years (545 days)*	7,9,13	2400
2 years (730 days)	2,7,9,13	2600
2.5 years (910 days)*	2,5,7,9	2300
3 years (1095 days)	2,5,7,9,11	3300
3.5 years (1275 days)*	2,5,7,9,11,13	4100
4 years (1460 days)	2,5,7,9,11,13,16	4600
4.5 years (1640 days)*	2,5,7,9,11,13,17	4500
5 years (1825 days)	2,5,6,7,9,11,13,16	5200

At 1.5 years, path 2 was replaced with path 3 when repair times were increased. At 2.5 years, the number of paths completed was reduced by one. This trend continues until year 4. At 3.5 years, path 16 was completed instead of path 13 in the previous trial. This is to be expected because path 16 has a larger benefit and lower repair cost.

Table 4.9 shows the results of the next trial with the repair time for the bridges increased by an additional 5%. The table is in the same format as Table 4.7.

Table 4.9 - Model Output for Continuity Test 7-Budget: $1,000,000

Time	**Paths completed**	**Recognized Benefit ($)**
6 months (180 days)	2	200
1 year (365 days) *	2,9	1100
1.5 years (545 days)*	2,7,13	1700
2 years (730 days)	2,7,9,13	2600
2.5 years (910 days)	2,5,7,9	2300
3 years (1095 days)*	5,7,9,11,13	3900
3.5 years (1275 days)	2,5,7,9,11,13	4100
4 years (1460 days)*	2,5,7,9,11,16	3800
4.5 years (1640 days)*	2,5,7,9,11,13,16	4600
5 years (1825 days)*	2,3,5,7,9,11,13,16	4900

The same number of paths were completed for each time period as in the previous trial except at 4 years. Only 6 paths were completed for Test 7. All but four of the time periods chose different paths than the Test 6 run. These were only minor changes and were expected as the repair time increases.

One more test was performed increasing the repair time by an additional 5%. This will be a total of a 15% time increase from Test 5 to Test 8. The results are shown in Table 4.10 and are in the same format as Table 4.7.

Table 4.10 - Model Output for Continuity Test 8-Budget: $1,000,000

Time	Paths completed	Recognized Benefit ($)
6 months (180 days)	2	200
1 year (365 days)	2,9	1100
1.5 years (545 days)	2,7,13	1700
2 years (730 days)*	2,7,9	1800
2.5 years (910 days)	2,5,7,9	2300
3 years (1095 days)	2,5,7,9,13	3100
3.5 years (1275 days)*	2,5,7,9,11	3300
4 years (1460 days)*	2,5,7,9,13,17	3500
4.5 years (1640 days)	2,5,7,9,11,13,16	4600
5 years (1825 days)*	2,5,7,9,11,13,17	4500

More changes similar to the ones in Test 7 occur in Test 8. There is a reduction in the total number of paths completed and some paths were chosen over previous ones. An example of this is at 4.5 years, paths 13 and 17 were chosen over paths 11 and 16, respectively, from the previous test. At every trial there have been changes due to the increased repair time. This indicates that the model is sensitive to changes in repair times. None of these changes is out of the ordinary. They are expected with an increase in repair times. The continuity check does not reveal any errors in the model.

Degeneracy Testing

Degeneracy testing consists of checking the use of the model for extreme cases of input parameters. To test the accuracy of the model at extreme conditions, two scenarios are modeled and compared. The first scenario includes all the bridges with extensive damage and a repair time of 90 days. The second scenario consists of all the bridges with complete damage and a repair time of 120 days. For both scenarios, the previous hypothetical highway network of 20 paths with 100 bridges given in Table 4.1 is used. This hypothetical network is also illustrated in Figure 4.1. The budget for the two scenarios is $1,000,000. It is expected that the second scenario will have fewer paths and bridges completed because of the increase in damage levels and therefore increased costs and time.

Table 4.11 reports the results from the first scenario with all the bridges having extensive damage. The first column denotes the time allowed for the repairs, the second column denotes the paths that can be completed within that time period and the third column denotes the benefit that is recognized when the paths in column two are completed.

Table 4.11 - Scenario 1-Extensive damage

Time	Paths completed	Recognized Benefit ($)
6 months (180 days)	None	0
1 year (365 days)	None	0
1.5 years (545 days)	17	400
2 years (730 days)	17	400
2.5 years (910 days)	7,17	1100
3 years (1095 days)	7,17	1100
3.5 years (1275 days)	7,17	1100
4 years (1460 days)	7,16,17	1600
4.5 years (1640 days)	7,16,17	1600
5 years (1825 days)	7,11,16,17	2600

Table 4.12 shows the results from the second scenario with each bridge having complete damage. The table is in the same format as Table 4.11.

Table 4.12 - Scenario 2-Complete damage

Time	Paths completed	Recognized Benefit ($)
6 months (180 days)	None	0
1 year (365 days)	None	0
1.5 years (545 days)	None	0
2 years (730 days)	17	400
2.5 years (910 days)	17	400
3 years (1095 days)	17	400
3.5 years (1275 days)	7,17	1100
4 years (1460 days)	7,17	1100
4.5 years (1640 days)	7,17	1100
5 years (1825 days)	7,16,17	1600

The second scenario when all the bridges are completely damaged requires 2 years before any paths can be completed. After 5 years only three paths are completed. The second scenario has a repair time of 33% more than the first scenario. Costs are also 25% higher in the second scenario versus the first scenario. Therefore it is expected that the number of paths completed would be reduced by approximately one. This is the outcome that is observed. The model passes the degeneracy test for validation.

Consistency Testing

Consistency checking consists of changing the workload within a system to see if similar characteristics in the output are observed based on the assumption that similarly loaded systems will exhibit similar characteristics. In the previous test for continuity, a highway system of 20 paths with 5 bridges each was used. The characteristics for that network are given in Table 4.1. By changing the system to a 10 path system with 10 bridges each, similar characteristics should be observed between continuity test 1 in Table 4.2 and consistency check 1 given in Table 4.13. The hypothetical network containing 10 paths with 10 bridges per path is shown in Figure 4.2. This is just one possibility of how the network could be configured.

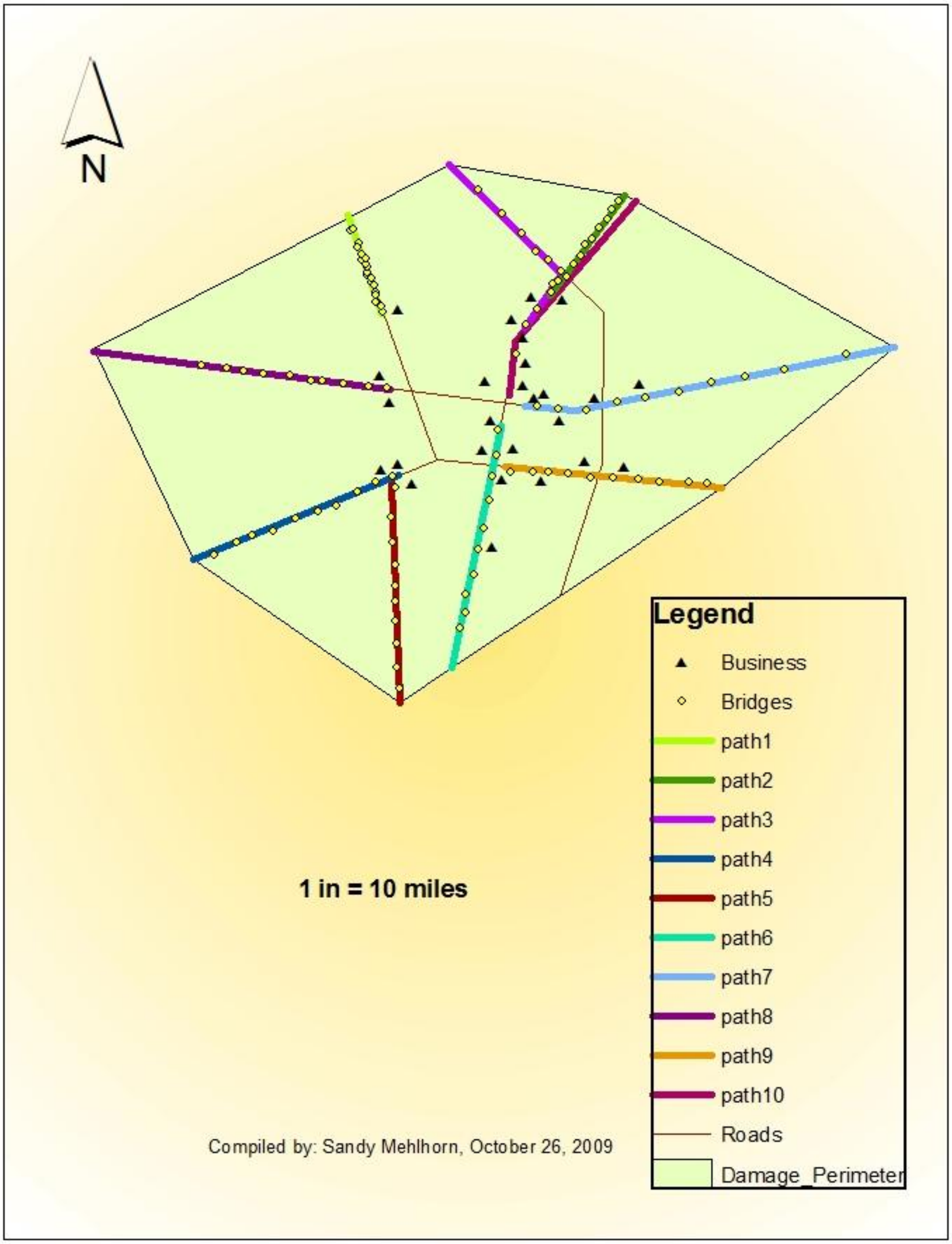

Figure 4.2-Example of Hypothetical Network with 10 Paths and 100 Bridges

The characteristics for the new network are given in Table 4.13 below. The first column gives the path number, the second column gives the number of bridges within each path, the third column is the sum of the repair cost for the bridges within the path, the fourth column is the sum of the repair time for the bridges within the path and the fifth column is the total benefit for completing the path.

Table 4.13 - Characteristics of 10 path-100 bridge network

Path No	Bridge No	Replace Cost	Damage Level	Bridge Repair Cost	Repair Time	Total Cost of Path	Benefit ($)
1	1	$1,107.69	slight	277	30		
	2	$2,029.34	complete	2029	120		
	3	$930.20	moderate	465	60		
	4	$3,261.06	none	500	10		
	5	$2,611.41	complete	2611	120		
	51	$1,604.66	extensive	1203	90		
	52	$1,965.33	moderate	983	60		
	53	$1,184.25	moderate	592	60		
	54	$1,184.25	none	500	10		
	55	$1,347.19	none	500	10	8161	1100
2	6	$2,702.51	slight	676	30		
	7	$4,105.87	none	500	10		
	8	$1,707.58	moderate	854	60		
	9	$754.43	none	500	10		
	10	$2,951.85	none	500	10		
	56	$1,347.19	complete	1347	120		
	57	$1,548.63	complete	1549	120		
	58	$1,548.63	none	500	10		
	59	$7,378.05	slight	1845	30		
	60	$6,170.14	slight	1543	30	7812	1100

Table 4.13 - Characteristics of 10 path-100 bridge network

Path No	Bridge No	Replace Cost	Damage Level	Bridge Repair Cost	Repair Time	Total Cost of Path	Benefit ($)
3	11	$2,095.63	slight	524	30		
	12	$648.65	slight	162	30		
	13	$3,795.23	complete	3795	120		
	14	$2,619.54	none	500	10		
	15	$1,852.14	slight	463	30		
	61	$3,944.78	none	500	10		
	62	$3,616.03	none	500	10		
	63	$5,161.53	moderate	2581	60		
	64	$2,460.73	none	500	10		
	65	$1,461.38	none	500	10	7525	1100
4	16	$1,481.91	moderate	741	60		
	17	$2,101.33	moderate	1051	60		
	18	$2,792.47	complete	2792	120		
	19	$1,596.67	complete	1597	120		
	20	$1,227.44	slight	307	30		
	66	$1,576.00	extensive	1182	90		
	67	$991.65	none	500	10		
	68	$1,149.89	none	500	10		
	69	$22,070.85	complete	22071	120		
	70	$4,148.50	moderate	2074	60	31815	1100
5	21	$1,766.32	none	500	10		
	22	$2,316.60	slight	579	30		
	23	$3,600.21	slight	900	30		
	24	$1,304.42	moderate	652	60		
	25	$492.97	extensive	370	90		
	71	$1,877.52	extensive	1408	90		
	72	$4,663.42	none	500	10		
	73	$2,628.52	complete	2629	120		
	74	$6,241.28	moderate	3121	60		
	75	$775.53	moderate	388	60	10046	1100

Table 4.13 - Characteristics of 10 path-100 bridge network

Path No	Bridge No	Replace Cost	Damage Level	Bridge Repair Cost	Repair Time	Total Cost of Path	Benefit ($)
6	26	$2,119.58	extensive	1590	90		
	27	$1,122.66	moderate	561	60		
	28	$1,368.58	moderate	684	60		
	29	$3,155.42	none	500	10		
	30	$1,240.84	complete	1241	120		
	76	$775.53	moderate	388	60		
	77	$814.30	moderate	407	60		
	78	$1,335.22	none	500	10		
	79	$2,359.94	extensive	1770	90		
	80	$1,184.39	slight	296	30	6937	1100
7	31	$1,847.29	slight	462	30		
	32	$958.86	slight	240	30		
	33	$1,204.63	moderate	602	60		
	34	$1,547.92	slight	387	30		
	35	$364.24	moderate	182	60		
	81	$581.64	none	500	10		
	82	$581.64	extensive	436	90		
	83	$772.82	complete	773	120		
	84	$772.82	moderate	386	60		
	85	$730.33	extensive	548	90	4016	1100
8	36	$111,110.69	slight	27778	30		
	37	$894.14	complete	894	120		
	38	$3,947.49	complete	3947	120		
	39	$2,408.69	moderate	1204	60		
	40	$2,408.69	moderate	1204	60		
	86	$730.33	slight	183	30		
	87	$1,553.90	moderate	777	60		
	88	$1,600.52	extensive	1200	90		
	89	$2,085.08	complete	2085	120		
	90	$5,227.11	complete	5227	120	44500	1100

Table 4.13 - Characteristics of 10 path-100 bridge network

Path No	Bridge No	Replace Cost	Damage Level	Bridge Repair Cost	Repair Time	Total Cost of Path	Benefit ($)
9	41	$1,212.47	none	500	10		
	42	$1,212.47	moderate	606	60		
	43	$1,005.90	extensive	754	90		
	44	$1,925.99	none	500	10		
	45	$2,720.76	none	500	10		
	91	$5,065.44	extensive	3799	90		
	92	$772.82	complete	773	120		
	93	$1,781.43	slight	445	30		
	94	$1,429.88	complete	1430	120		
	95	$640.81	moderate	320	60	8129	1100
10	46	$1,780.86	slight	445	30		
	47	$2,226.07	complete	2226	120		
	48	$1,335.64	slight	334	30		
	49	$8,119.08	slight	2030	30		
	50	$7,378.05	extensive	5534	90		
	96	$738.03	complete	738	120		
	97	$3,286.72	none	500	10		
	98	$3,286.72	extensive	2465	90		
	99	$1,801.39	none	500	10		
	100	$1,017.88	moderate	509	60	14281	1100

This network combines paths from the previous network. Paths 1 and 11 were combined as well as paths 2 and 12, 3 and 13, 4 and 14, 5 and 15, 6 and 16, 7 and 17, 8 and 18, 9 and 19, as well as 10 and 20 to form the new network. This does cause the benefit for each path to be $1100 which could skew the results. Since there is no benefit of one path over another, the model will revert to the cost and time aspects only of the model. Table 4.14 shows the results from the first trial of the network given in Table 4.13. The first column denotes the time allowed for the repairs, the second column denotes the paths that can be completed within the given time period and the third column is the benefit recognized when the paths are completed.

Table 4.14 - Output from 10 path network with 100 bridges-Budget: $1,000,000

Time	Paths completed	Recognized Benefit ($)
6 months (180 days)	none	0
1 year (365 days)	3	1100
1.5 years (545 days)	2	1100
2 years (730 days)	7	1100
2.5 years (910 days)	3,7	2200
3 years (1095 days)	2,7	2200
3.5 years (1275 days)	6,7	2200
4 years (1460 days)	2,3,7	3300
4.5 years (1640 days)	2,6,7	3300
5 years (1825 days)	6,7,9	3300

It is expected that the model would choose approximately half the number of paths as the first network run because the second network contains twice the number of bridges per path. The output is consistent with this expectation.

Summary of validation of the model

After performing the various validation tests, there appears to be no obvious errors in the model. Table 4.15 below provides a summary of the various validation tests and the outcome of each. These outcomes were all were expected for the various tests.

Table 4.15-Summary of Validation Testing

Validation Test	Purpose of the Test	Expectation of the Outcome	Outcomes
Continuity Testing	Check for significant changes in output with only slight changes in input	Should notice only slight changes in output with slight changes in input	1. With increased repair costs, there are no large changes observed in the output that would indicate an error in the model 2. With increased repair times, there are no large changes observed in the output that would indicate an error in the model 3. The model does not appear sensitive to the repair cost input as much as the repair time input
Degeneracy Testing	Test the extreme values of the system and input parameters	The worst-case scenario should allow less repair to be done in allowed time periods	1. The scenario with complete damage to all bridges required 33% more time with 25% more repair cost. Therefore one bridge less was repaired in the total allowed time period for the most extreme case.
Consistency Testing	Changes the workload to check that a model produces similar output for similar inputs	Should have half the number of paths repaired because the number of bridges per path is doubled	1. Model showed repairs on half the number of paths for the 10 path/ 100 bridge network as for the 20 path/100 bridge network, which is an expected outcome.

Model Demonstration for Shelby County, Tennessee

When determining which routes should be repaired first in the current demonstration, priority is being given to business because studies have revealed that the restoration of the highway network is directly related to the economic recovery of an area. For Shelby County, a large majority of the key revenue producing companies are located in the southern portion of the county. Key businesses are identified for this research as the top 25 revenue producing industries for the fiscal year 2007 (Bolton 2008). Using ArcGIS, the shortest route along the designated highways from each industry to the edge of the county was determined. These “shortest routes” are the paths designated within the model. Because so much of the business is clustered together, a total of 9 paths are identified for the 25 businesses. It is assumed that once the freight reaches the edge of the county, it is outside the damage perimeter and can travel on any roadway in any direction necessary. This assumption may cause increased travel times for some businesses in practical application. This assumption is addressed further in the limitations of the model at the end of this chapter. Each path contains various numbers of bridges. Roadways and streets designated as a US Highway, as well as interstates are used within the model. These roads are included because freight traffic currently uses these routes and all bridges are posted for heavy vehicles. Figure 4.3 shows Shelby County with the location of businesses, paths, bridges and roadways used for this demonstration. Table 4.16 summarizes the characteristics for the nine paths designated in Shelby County. The first column is the path number, the second column is the number of bridges within that path and the third column is the benefit recognized when the path is completed.

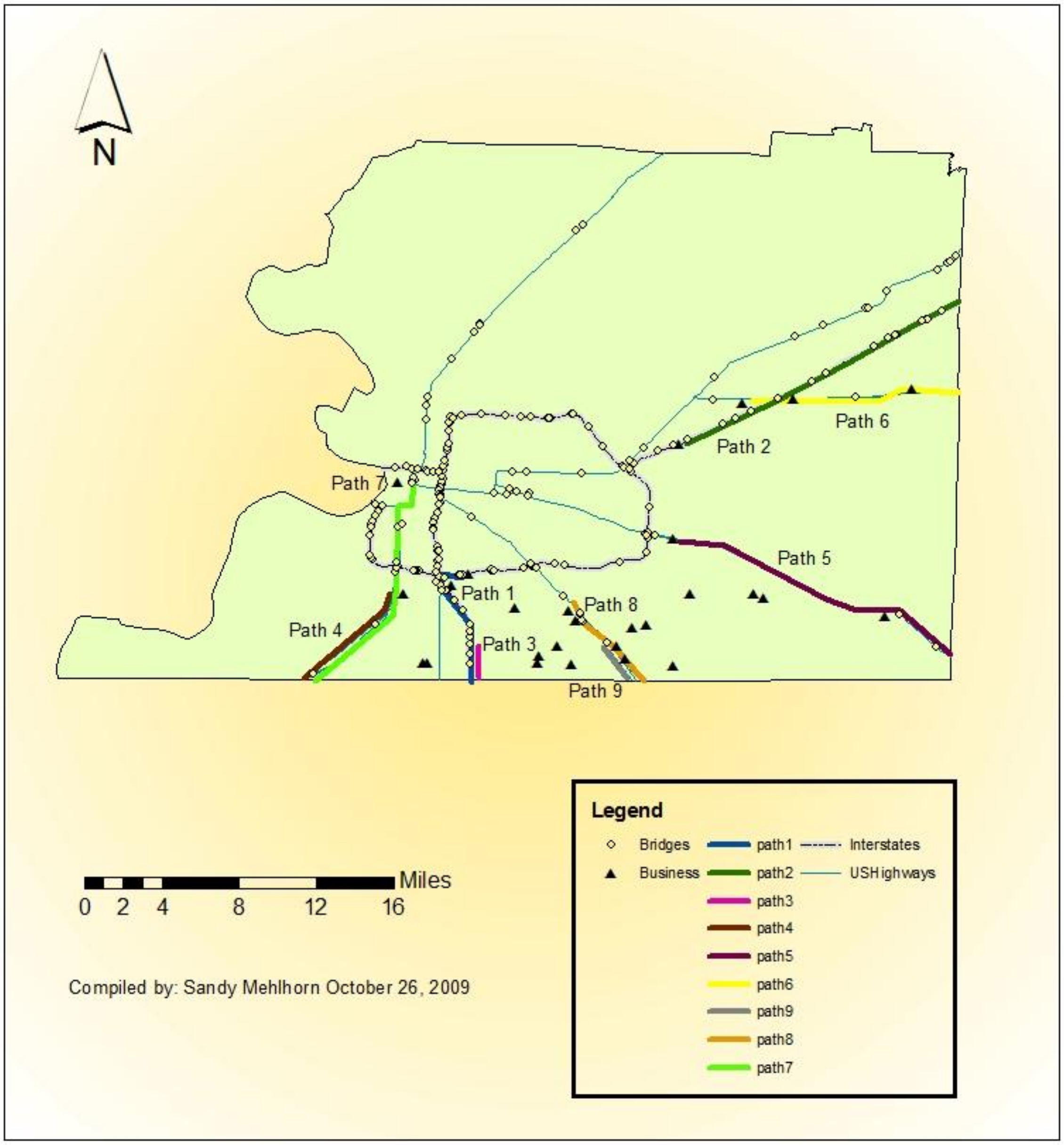

Figure 4.3- Locations of Businesses, Bridges and Paths for Shelby Count

Table 4.16 – Characteristics of Paths for Shelby County

Path number	No. of bridges in path	Benefit (million $)
1	5	13500
2	20	44500
3	15	3400
4	5	9600
5	3	81600
6	2	5700
7	12	6200
8	9	166298.3
9	2	116025.5

For this research, the benefit is the sum of the fiscal year revenue for each business using the path. This allows a weighting factor for the path based on the importance to the regional economy each business contributes. The other characteristics for each path and the source of the data are discussed in the methodology chapter.

When an area has been declared a federal disaster area, monies are typically distributed from the federal government in 2 year or more increments (United States Department of Transportation 2009). To illustrate the various outputs for differing budgets and time periods, several scenarios were modeled keeping all parameters constant except budget. The first trial used a budget of

$10,000,000 and time periods of 6 month increments over a 5 year period. After the trial run, the budget was increased to $20,000,000 and re-run for the same time periods. Three additional trials were performed increasing the budget by $10,000,000 up to a total of $50,000,000. For each trial the bridge damage levels, cost of repairs, time of repairs and benefits for each path were held constant. A complete list of the bridge conditions (i.e. bridge repair costs and repair times) are given in Appendix B. Two demonstrations are shown for different levels of bridge damage. These levels of damage were randomly assigned within an Excel spreadsheet for this demonstration. The levels of damage are reported in the same format as output from FEMA's HAZUS-MH software. Each trial computed the paths that could be completed to fulfill the objective function of maximum benefit and then a minimum path constraint was added to compute the minimum number of paths that could be completed given the time and budget constraints. The minimum path constraint allows the user to predetermine the minimum number of paths that must be constructed and therefore allows the user to force the model to find at least a specified number of paths that can be completed with the given budget and time constraints. This constraint is important in comparing the results of a purely maximized benefit output versus an output that is required to complete a minimum number of paths. The results from the two scenarios are shown in the tables below.

The tables are designed to give the reader an understanding of the output from the model and how the various inputs affect the output.

Shelby County Scenario A:

- Budget increased in $10,000,000 increments with each trial
- Time increased in 6 month increments up to 5 years for each budget
- 15% of bridges not damaged, 17% slightly damaged, 22% moderately damaged, 22% extensively damaged and 22% completely damaged

Figure 4.4 provides a visual aid for the network status of this scenario. It shows the location of the paths along with the damage levels of the bridges on those paths.

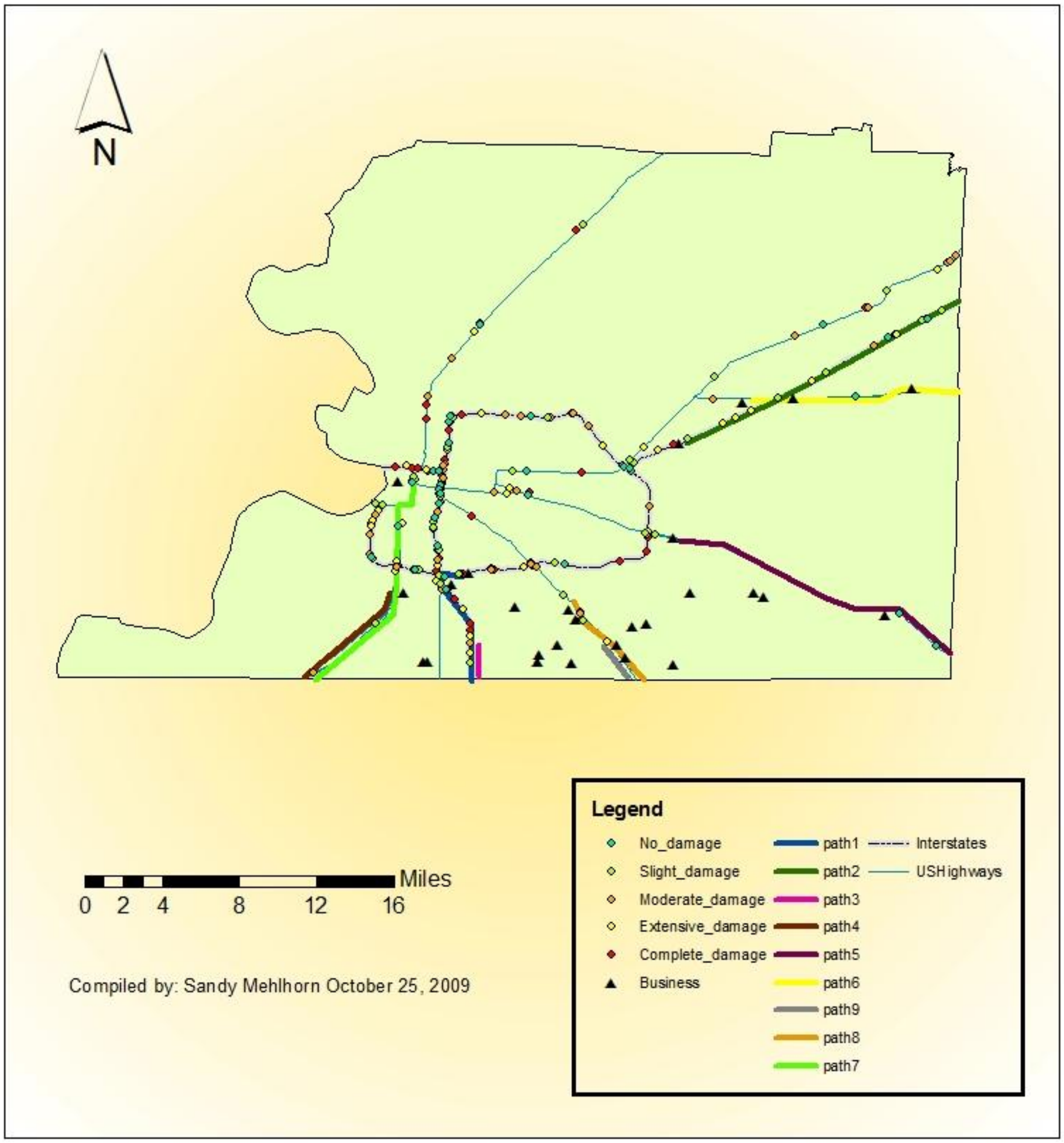

Figure 4.4 – Bridge Damage Levels for Scenario A

Table 4.17 shows the results from the first run of Scenario A. The first column denotes the time allowed for the repairs, the second column denotes the paths that can be completed by maximizing benefit, the third column gives the benefit that is recognized when the paths are completed, the fourth column denotes the paths that can be completed by maximizing the number of paths to be completed and the fifth column denotes the benefit recognized by completing the paths.

Table 4.17 - Trial 1-Budget $10,000,000

	Maximum Benefit		Maximum No. of Paths	
Time	**Paths completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,6,9	203325.5	5,6,9	203325.5
1.5 years	5,6,8	253598.3	5,6,8	253598.3
2 years	8,9	282324	1,5,6,9	216825.5
2.5 years	8,9	282324	1,5,6,9	216825.5
3 years	8,9	282324	1,5,6,9	216825.5
3.5 years	8,9	282324	1,5,6,9	216825.5
4 years	8,9	282324	1,5,6,9	216825.5
4.5 years	8,9	282324	1,5,6,9	216825.5
5 years	8,9	282324	1,5,6,9	216825.5

For Trial 1, two paths can be completed within a six month time frame but increasing the time to one year allows an extra path to be completed. When the model is computing the maximum benefits, from 2 to 5 years, it is recommended to only complete paths 8 and 9 to maximize the benefit. However, if a minimum path constraint is added, a total of four paths can be completed in the same time frame. Paths 1, 5, 6 and 9 can be completed with a benefit of $216,825,500,000. This is a lesser benefit than by completing paths 8 and 9 but more paths are able to be completed. The four paths completed from the 2 to 5 year time period have a smaller benefit than completing paths 5, 6 and 8 at 1.5 years.

Table 4.18 shows the results from Trial 2 of Scenario A with an increased budget. The table is in the same format as Table 4.17.

Table 4.18 - Trial 2-Budget $20,000,000

	Maximum Benefit		**Maximum No. of Paths**	
Time	**Paths Completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,6,9	203325.5	5,6,9	203325.5
1.5 years	5,6,8	253598	4,5,6,9	212925.5
2 years	5,6,8,9	369623.8	5,6,8,9	369623.8
2.5 years	5,6,8,9	369623.8	1,4,5,6,9	226425.5
3 years	1,5,8,9	377424	1,4,5,6,9	226425.5
3.5 years	1,5,6,8,9	383123.8	1,5,6,8,9	383123.8
4 years	1,5,6,8,9	383123.8	1,5,6,8,9	383123.8
4.5 years	1,5,6,8,9	383123.8	1,5,6,8,9	383123.8
5 years	1,5,6,8,9	383123.8	1,5,6,8,9	383123.8

With the increased budget in Trial 2, more paths are able to be completed within the same time periods as Trial 1. After 5 years, a total of 5 paths can be completed with a benefit of $383,123,800,000. This is the same result obtained with the minimum path constraint for this trial. It is interesting to note that when the model is forced to complete a certain number of paths, the benefit slowly increases until it spikes at time 2 years but then it falls a significant amount at 2.5 years. Then at 3.5 years, it reaches its maximum benefit and maximum number of paths that can be completed.

Table 4.19 gives the results from Trial 3 of Scenario A with an increased budget. The table is in the same format as Table 4.17.

Table 4.19 - Trial 3-Budget $30,000,000

	Maximum Benefit		Maximum No. of Paths	
Time	**Paths Completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,6,9	203325.5	5,6,9	203325.5
1.5 years	5,6,8	253598	4,5,6,9	212925.5
2 years	5,6,8,9	369623.8	5,6,8,9	369623.8
2.5 years	5,6,8,9	369623.8	1,4,5,6,9	226425.5
3 years	4,5,6,8,9	379223.8	4,5,6,8,9	379223.8
3.5 years	4,5,6,8,9	379223.8	4,5,6,8,9	379223.8
4 years	1,4,5,6,8,9	392723.8	1,4,5,6,8,9	392723.8
4.5 years	1,4,5,6,8,9	392723.8	1,4,5,6,8,9	392723.8
5 years	1,4,5,6,8,9	392723.8	1,4,5,6,8,9	392723.8

With the additional budget in Trial 3, an extra path can be completed over the five year time period. Path 4 is added to the completed paths from Trial 2. This addition adds more benefit and provides more accessibility to more businesses. After 3 years, the same paths are chosen for providing maximum benefit and for completing the maximum number of paths. This is six months earlier than in Trial 2. Notice again that the benefit spikes at 2 years when the model is being forced to complete the maximum number of paths possible.

Table 4.20 shows the results from Trial 4 of Scenario A with an increased budget. The table is in the same format as Table 4.17.

Table 4.20 - Trial 4-Budget $40,000,000

	Maximum Benefit		**Maximum No. of Paths**	
Time	**Paths completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,6,9	203325.5	5,6,9	203325.5
1.5 years	5,6,8	253598	4,5,6,9	212925.5
2 years	5,6,8,9	369623.8	5,6,8,9	369623.8
2.5 years	5,6,8,9	369623.8	1,4,5,6,9	226425.5
3 years	4,5,6,8,9	379223.8	4,5,6,8,9	379223.8
3.5 years	4,5,6,8,9	379223.8	4,5,6,8,9	379223.8
4 years	1,4,5,6,8,9	392724	4,5,6,7,8,9	385423.8
4.5 years	1,4,5,6,8,9	392724	4,5,6,7,8,9	385423.8
5 years	1,4,5,6,7,8,9	398924	1,4,5,6,7,8,9	398923.8

The results for Trial 4 are the same as Trial 3 until 3.5 years. At that time, the model chooses different paths for completion. To increase the benefit, Path 1 is for completion in addition to Paths 4,5,6,8 and 9. When the model is determining the maximum number of paths to be completed, Path 7 is chosen over Path 1 at four years even though the benefit is less for completing this path and the benefit spikes at 2 years just as in the previous trials. At five years, seven paths are completed with a total benefit of $398,924,000,000.

Table 4.21 gives the final results for Scenario A. The budget has been increased to a total of $50,000,000. The table is in the same format as Table 4.17.

Table 4.21 - Trial 5-Budget $50,000,000

	Maximum Benefit		Maximum No. of Paths	
Time	Paths completed	Recognized Benefit (million $)	Paths completed	Recognized Benefit (million $)
6 months	5,6	87300	5,6	87300
1 year	5,6,9	203325.5	5,6,9	203325.5
1.5 years	5,6,8	253598	4,5,6,9	212925.5
2 years	5,6,8,9	369623.8	5,6,8,9	369623.8
2.5 years	5,6,8,9	369623.8	1,4,5,6,9	226425.5
3 years	4,5,6,8,9	379223.8	4,5,6,8,9	379223.8
3.5 years	4,5,6,8,9	379223.8	4,5,6,8,9	379223.8
4 years	1,4,5,6,8,9	392724	4,5,6,7,8,9	385423.8
4.5 years	1,4,5,6,8,9	392724	4,5,6,7,8,9	385423.8
5 years	1,4,5,6,7,8,9	398923.8	1,4,5,6,7,8,9	398923.8

Trial 5 results are the same as Trial 4. The budget increase from $40,000,000 to $50,000,000 did not make any changes in the paths chosen over the five year time period. There are only two paths that remain uncompleted.

Every trial shows that paths 5 and 6 should be completed first and can be completed within the initial 6 month time period. Path 9 is the next to be completed in every trial.

For the next demonstration, all bridge damage levels were increased one level from Scenario A. Again the model was run for maximum benefit and then run again with a minimum path constraint that allows the user to force the model to choose the maximum number of paths that can be completed given the time and budget constraints.

Shelby County Scenario B:

- Budget increased in $10,000,000 increments with each trial
- Time increased in 6 month increments up to 5 years for each budget
- 0% of bridges not damaged, 16% slightly damaged, 17% moderately damaged, 23% extensively damaged and 44% completely damaged

Figure 4.5 shows the bridge damage levels demonstrated in this scenario and their locations on the paths.

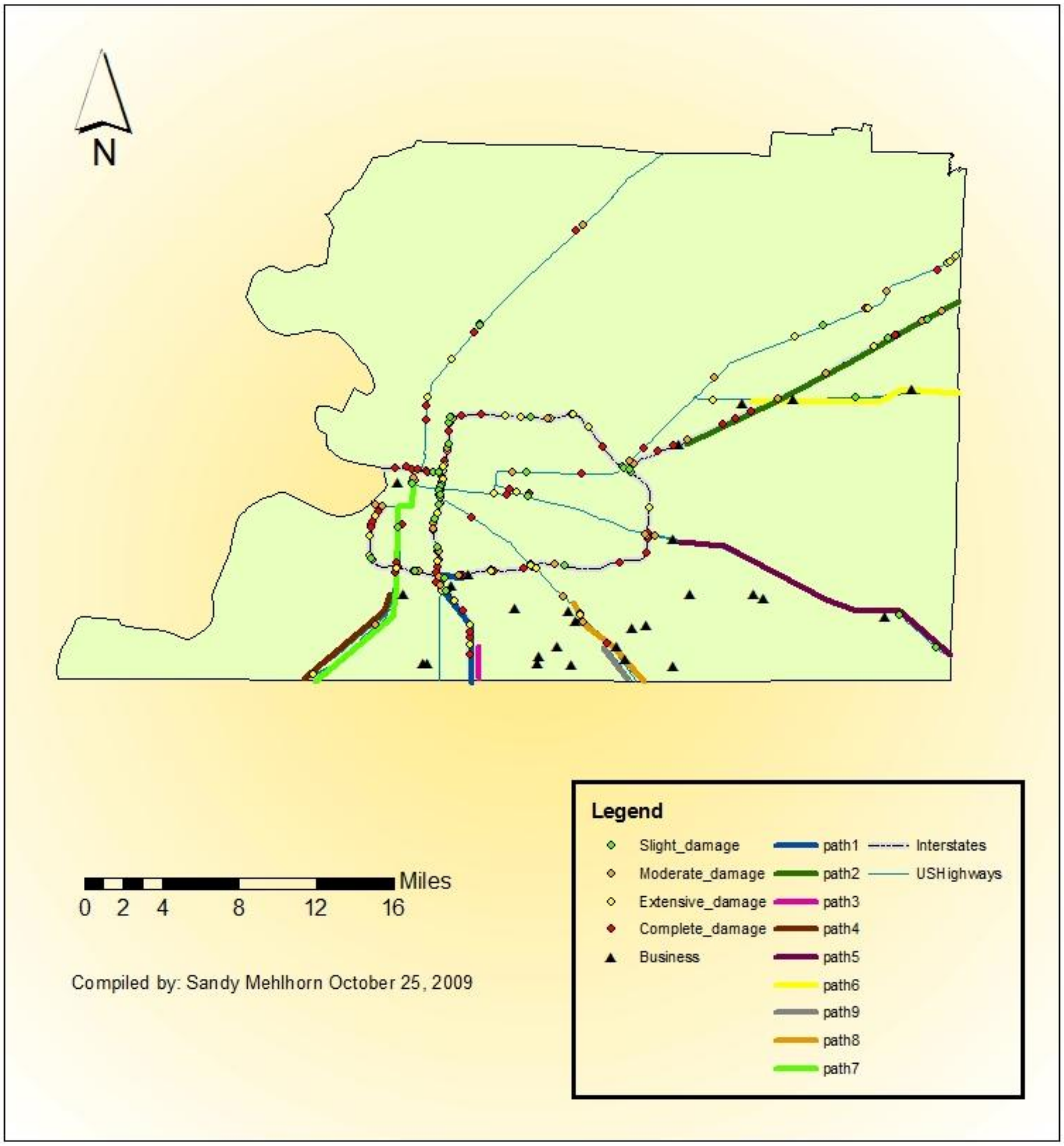

Figure 4.5-Bridge Damage Levels for Scenario B

Table 4.22 shows the results from Trial 1 of Scenario B. This output is in the same format as the tables for Scenario A. The characteristics for each path are given in Table 4.16.

Table 4.22 - Trial 1-Budget $10,000,000

	Maximum Benefit		Maximum No. of Paths	
Time	**Paths completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,9	197625.5	5,9	197625.5
1.5 years	5,6,9	203325.5	5,6,9	203325.5
2 years	5,6,9	203325.5	5,6,9	203325.5
2.5 years	1,5,9	211125.5	1,5,9	211125.5
3 years	5,8	247898	1,5,6,9	216825.5
3.5 years	5,6,8	253598	1,5,6,9	216825.5
4 years	5,6,8,9	369623.8	5,6,8,9	369623.8
4.5 years	5,6,8,9	369623.8	5,6,8,9	369623.8
5 years	5,6,8,9	369623.8	5,6,8,9	369623.8

Within the first six months, only two paths can be completed. Increasing the time period to one year does not increase the number of paths but Path 9 is given priority for completion before Path 6. Path 6 is completed in addition to Path 5 and 9 when the time is increased to 1.5 and 2 years. When only maximizing benefit, at 3 years, Path 8 is chosen for completion with Path 5. Even though only two paths are being completed, the benefit is greater than completing the previous three paths. At the same time period, when choosing the maximum number of paths that can be completed, four paths are completed.

At the final 5 year period, the same four paths are chosen in both cases with a total benefit of $369,623,800,000. For this trial, the benefit does not spike for completing the maximum number of paths as it has in the previous trials.

Table 4.23 shows the results from Trial 2 of Scenario B. The difference between Trial 1 and Trial 2 is an increased budget. The table is in the same format as Table 4.17.

Table 4.23 - Trial 2-Budget $20,000,000

	Maximum Benefit		**Maximum No. of Paths**	
Time	**Paths completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,9	197625.5	5,9	197625.5
1.5 years	5,6,9	203325.5	5,6,9	203325.5
2 years	5,6,9	203325.5	5,6,9	203325.5
2.5 years	1,5,9	211126	5,6,9	203325.5
3 years	5,8	247898	1,5,6,9	216825.5
3.5 years	5,6,8	253598	1,5,6,9	216825.5
4 years	5,6,8,9	369623.8	5,6,8,9	369623.8
4.5 years	5,6,8,9	369623.8	5,6,8,9	369623.8
5 years	5,6,8,9	369623.8	1,4,5,6,9	226425.5

Trial 2 results are identical to Trial 1 results in relation to the maximum benefit calculations. For the calculation of the maximum number of paths that can be completed, the results are identical except for year 2.5 when Path 6 is chosen over Path 1 for completion. The additional budget is a contributing factor in this choice. However, Path 1 is back in the priority list at 3 years. With the given budget, a maximum number of five paths are able to completed although the benefit is less than the four paths chosen by the maximum benefit calculations.

Table 4.24 shows the results from Trial 3 of Scenario B with an increased budget. The table is in the same format as Table 4.17.

Table 4.24 - Trial 3-Budget $30,000,000

	Maximum Benefit		Maximum No. of Paths	
Time	**Paths completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,9	197625.5	5,9	197625.5
1.5 years	5,6,9	203325.5	5,6,9	203325.5
2 years	5,6,9	203325.5	5,6,9	203325.5
2.5 years	1,5,9	211126	5,6,9	203325.5
3 years	5,8	247898	1,5,6,9	216825.5
3.5 years	5,6,8	253598	1,5,6,9	216825.5
4 years	5,6,8,9	369623.8	5,6,8,9	369623.8
4.5 years	5,6,8,9	369623.8	5,6,8,9	369623.8
5 years	5,6,8,9	369623.8	1,4,5,6,9	226425.5

Trial 3 is identical to the results for Trial 2. Therefore it can be concluded that the additional budget is not helpful for the given scenario. Time is the limiting factor in completing more paths.

Table 4.25 shows the results from Trial 4 of Scenario B. The table is in the same format as Table 4.17.

Table 4.25 - Trial 4-Budget $40,000,000

	Maximum Benefit		Maximum No. of Paths	
Time	**Paths completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,9	197625.5	5,9	197625.5
1.5 years	5,6,9	203325.5	5,6,9	203325.5
2 years	5,6,9	203325.5	5,6,9	203325.5
2.5 years	1,5,9	211126	5,6,9	203325.5
3 years	5,8	247898	1,5,6,9	216825.5
3.5 years	5,6,8	253598	1,5,6,9	216825.5
4 years	5,6,8,9	369623.8	5,6,8,9	369623.8
4.5 years	5,6,8,9	369623.8	5,6,8,9	369623.8
5 years	5,6,8,9	369623.8	1,4,5,6,9	226425.5

Trial 4 is identical to Trial 3 and Trial 2. Time is still too limited to allow the completion of more paths.

Table 4.26 shows the results from the final trial of Scenario B. The budget has been increased to a total of $50,000,000. The table is in the same format as Table 4.17.

Table 4.26 - Trial 5-Budget $50,000,000

	Maximum Benefit		Maximum No. of Paths	
Time	**Paths completed**	**Recognized Benefit (million $)**	**Paths completed**	**Recognized Benefit (million $)**
6 months	5,6	87300	5,6	87300
1 year	5,9	197625.5	5,9	197625.5
1.5 years	5,6,9	203325.5	5,6,9	203325.5
2 years	5,6,9	203325.5	5,6,9	203325.5
2.5 years	1,5,9	211126	5,6,9	203325.5
3 years	5,8	247898	1,5,6,9	216825.5
3.5 years	5,6,8	253598	1,5,6,9	216825.5
4 years	5,6,8,9	369623.8	5,6,8,9	369623.8
4.5 years	5,6,8,9	369623.8	5,6,8,9	369623.8
5 years	5,6,8,9	369623.8	1,4,5,6,9	226425.5

Extending the budget to $50,000,000 still does not allow more paths to be completed. More than 5 years would be needed to complete more than 5 paths for the given scenario.

By comparing the tables with various budgets and time periods, these scenarios can be used by transportation agencies or planning organizations for determining which routes to spend money for bridge retrofitting, other maintenance dollars or for disaster recovery plans.

For the demonstration in Shelby County, only nine paths are identified with 218 bridges. To test the robustness of the model, data was randomly generated for various numbers of paths and bridges. Table 4.27 summarizes the characteristics for the other test runs of the model. The first column denotes the number of paths that were used and the second column gives the total number of bridges that are located on those paths.

Table 4.27 – Various Characteristics of Other Test Runs

Number of Paths	**Number of Bridges**
400	5000
500	500
16,383	500

The model still performed quickly and efficiently, and the paths were able to be prioritized using the model. Because there are fewer bridges per path, total repair cost per path is less. This demonstrates the ability of the model to handle large, complex transportation systems. The maximum number of paths tested, 16,383, is the maximum number of columns allowed in an Excel spreadsheet that was used for these tests. If more than this number of paths are needed within a highway network, a Microsoft Access database or similar software would need to be used that does not limit the number of columns of data.

Limitations of the model

Although the model developed by this research has shown to be very flexible and able to handle large transportation systems, limitations exist. When using the model for planning purposes, limitations include estimating the perimeter of damage. This is important for determining where paths end. The length of the path determines the transportation components contained within that path, and therefore repair time and costs for the path. For this research, the path was determined by ArcGIS as the shortest path from the business to the edge of the county. This could be a problem if the damaged extended beyond the county borders. Other methods for estimating the perimeter of damage include using simulation software for various types of disasters or using historical data. If an event has occurred sometime in the past in the same area, research on the extent of the damage area could be used.

Using the shortest path method also leads to another limitation within these results. For some businesses, this method may route them to the south side of the county when most of their freight needs to travel north. This can result in increased travel times for the business. This directional bias could be addressed in the choice of the path for the business. Instead of using the shortest path from the business to the edge of the damage perimeter, the most traveled route for the business could be used as the path. Travel times could also be increased if the freight travels on a roadway with a lower capacity than the pre-disaster roadways they used. Roadway capacity is not considered in this model but should be incorporated into future research. The capacity of a certain roadway can drastically affect the movement of goods after a disaster if much more traffic is forced upon the road than it is capable of handling.

For disaster planning, the estimation of the repair cost and time is another limitation. Estimates need to be based on past bridge projects or regional information. These estimates will be affected by availability of resources should an actual event occur. Keeping a current database will help alleviate some of the problems that can occur with inaccurate data. If cost information is not current, it could be estimating low values for repairs. This could skew the output by the model.

Excel was used for a number of purposes in this research. Each path within the model uses a column within an Excel spreadsheet for transportation component information such as damage levels, repair costs and repair times. Also Excel spreadsheets are used to list each path and the benefit associated with that path. The limited number of columns in an Excel spreadsheet can limit the number of paths for a given highway network. If more than 16,383 paths are established for an area, another program such as Microsoft Access database will have to be used. These types of database programs do not limit the number of columns that can be used.

Because the businesses for this research are not all located directly on the US highways or interstates, another limitation is realized. The roads between the business and the roadways considered for the research may be severely damaged and require repairs before the freight can reach the recommended path. For this demonstration, the roads were assumed passable but that may not be the case in an actual disaster. This limitation would have to be addressed if the model from this research were to be used in an actual situation.

This model is an important first step in establishing an effective recovery plan for highway networks even though it is a simplified version. There are avenues for future research to make the model more comprehensive through expanded capacity analysis of the roadways pre-disaster, adding more objectives to the model to make it multi-objective, and more analysis of directional travel for businesses to make the paths more realistic to pre-disaster freight travel.

Chapter 5

Conclusions and Recommendations

Limited research has been performed on the recovery of transportation systems after a natural disaster. Former studies have looked at comparisons of restoration techniques for highway systems but have not extended to recommendations for restoration strategies. The current research establishes a framework for decision-making for transportation officials by providing a model that can be used for prioritizing routes for reconstruction. This concept is demonstrated using a case study in Shelby County, Tennessee giving priority to reconstruction of the highway network serving the top 25 revenue producing businesses in the county. The top 25 revenue producing businesses were chosen for priority based on prior research efforts that have shown how important economic recovery is to the overall recovery of a disaster-stricken area. This research is an important continuation of research that has been conducted for estimating the damage from natural disasters. It provides an important tool for transportation and planning agencies in establishing a recovery plan for the reconstruction of highway systems using damage estimations for a pre-disaster scenario.

Conclusions Regarding Model Performance

The model developed in this research provides state and local officials the opportunity to select entities that should be given priority for the reconstruction of roadways. Several general scenarios were performed to test and validate the model. A hypothetical highway network of 20 paths with 5 bridges on each path was used for extensive validation of the model. The results of the tests indicated that the model was more sensitive to time of repairs than cost of repairs for the individual components within a path. This was demonstrated in the validation of the model as well as the various scenarios for Shelby County. For example, in Table 4.11 results are shown for the model output given every bridge in the hypothetical network has extensive damage. The results show that no paths can be completed within the first year but after 5 years, four paths are completed. Table 4.12 shows the results when the bridge damage is increased one level to complete damage. For this scenario, no paths can be complete for 1.5 years and after 5 years, only three paths are completed. In contrast to this, Table 4.2 shows the model output for a given highway network. After 5 years, nine paths are completed. Table 4.5 shows the same highway network but repair cost to the bridges has been increased 20%. Even with the increased repair cost, eight bridges are completed after 5 years. Also, with the same budget, paths are always able to be completed within the minimum 6 month time period shown. These results demonstrate the sensitivity of the model to repair times more than repair costs. For further testing of the range of the model, various sizes of hypothetical networks were used ranging from nine paths with 218 bridges to 400 paths with 5,000 bridges and even 16,383 paths with 500 bridges. For these networks, various levels of bridge damage were randomly generated. A summary of these networks is given in Table 4.27. By varying the damage levels of the bridges, it more closely simulates outcomes from a real disaster.

An important aspect of the model is the budget available for restoration of the transportation network. Budgets are very crucial to most agencies because of the limited funds typically available. Because of the many sources of funds available to different agencies, estimating this factor in the model is difficult. Agencies may receive funds from federal agencies, state agencies or local taxpayers as a specified line item in the local transportation budget. Budgets are widely variable and will change depending on the region. Most transportation agencies are on a strict budget, therefore it is very important to them to spend it efficiently. The model presented in this research allows users to determine how to spend money efficiently based on the priorities they have set in advance.

The time aspect of the model is a key component in determining how money could be spent over a certain period of time. This aspect allows evaluation of a variety of 'what if' scenarios including an opportunity for agencies to evaluate different definitions of priority. It provides a tool to transportation agencies to measure achievement and to be able to demonstrate the planning process, budget allocation, and progress towards goals to the public. It is also a practical planning tool when combined with the budget aspect for preparing reports for agencies requesting funding from outside sources.

Conclusions Regarding Model Implementation

The model developed in this research provides a framework for decision-making in prioritizing the reconstruction of roadways after a natural disaster It can be used for planning or after a disaster has occurred. It has been shown to be flexible for various outcomes from natural disasters.

The key to successful implementation and application of the model is a good database of the highway network and related components in the area. The database should include the location of the transportation components and replacement costs. This database should be well maintained so that accurate information is available in the event of a disaster. Another key to successful implementation is developing a priority ranking system prior to a disaster that spells out which entities will be considered in the reconstruction of the roadways. Local agencies must decide who should be given priority for access. Typically, entities such as hospitals, schools, residential areas or business parks are those where the restoration of transportation accessibility is critical. Each locality is different and will use different processes for making this decision. Additional consideration should be given to identifying key transportation routes once priority entities are established. This information would help improve the reconstruction strategy by having paths in the model that are the most important for that entity versus just the shortest path to the perimeter of damage.

The implementation of the model can be applied by state and local transportation agencies in several contexts. The first is for the spending of maintenance dollars. If a possible damage scenario were modeled and the priority routes chosen, maintenance dollars could be spent first on the identified routes to improve their ability to sustain damage and remain viable. This could reduce both the damage sustained to the transportation components and the repair times after a disaster. The maintenance dollars could be spent on things such as retrofitting bridges for seismic activity or replacing a bridge deck. The model could also be usefully implemented to save time after a disaster on decision-making. It is important to have a recovery plan in place before a disaster strikes so that reconstruction can be implemented much more quickly and efficiently in the aftermath.

Once the model is implemented and the paths are chosen for priority reconstruction, a heuristic approach is necessary for the final decision-making. As demonstrated in the results chapter of this research, the model can be modified to choose the maximum number of paths that can be completed within a given time period and with a given budget. These paths may not be the same as the paths chosen to fulfill the objective function for maximizing benefit. This is shown in the output in Table 4.16. For maximizing the benefits, paths 8 and 9 were chosen for priority reconstruction. However, when the model is forced to choose the maximum number of paths that can be completed, Paths 1, 5, 6 and 9 are chosen. The benefit is lower but two more paths are completed. The heuristic approach would require the state and local agencies to determine which they feel has the most advantages to their area: maximum benefit or more paths. These decisions would be unique to each area and cannot be determined for every region in the same manner.

Recommendations

In order to avoid time consuming data gathering should an event occur, it is recommended that state and local transportation agencies keep a current database of transportation components in their area and approximate replacement cost. The location of all these components is also necessary. Other decisions that should be made in advance include which roadways will be considered for priority reconstruction (i.e. interstates, US highways, city streets). This information along with the corresponding transportation components and cost information can be easily stored in a GIS database until an event occurs.

When using the model for planning purposes, it is important to have accurate damage data from previous natural disasters or simulation software. Two different software packages mentioned in this research, HAZUS and REDARS, could give accurate data with additional time spent on collecting accurate up-to-date information for the study area. The time spent would be worthwhile for being able to plan for damage estimates during a disaster in order to plan maintenance and retrofitting of bridges along important routes.

Future Research

This model chooses routes for reconstruction after a natural disaster. Each route has various transportation components within it. Future research should be focused on the scheduling of the repairs to those components to most efficiently complete the path. Also studies in the change in travel times due to the path choices versus the paths traveled by the industries pre-event would be worthwhile. For example if a truck is forced to travel on a path that takes it to the southern part of the damage perimeter and the freight will be delivered north of the area, what would be the additional travel times and associated impact? Also, how many businesses are using a roadway and how does that affect the travel times as related to capacity of the roadway? This model could be expanded to incorporate measures of capacity that could also be used to constrain results based on viable solutions.

Another suggestion for future research is the feasibility of public-private partnerships for completing the repairs. Industries that rely on freight shipments for getting supplies or for shipping their product have a vested interest in the condition of the highway network. Agreements between state and local agencies and the private sector could prove beneficial to both parties.

For ease of implementation, a user interface could also be developed. By constructing a user interface for the model, the need for programming knowledge to implement the model would be eliminated. A user interface could possibly be created in a programming software such as MATLAB , Excel or Microsoft Access Database. Also, by running the model in one of these software, additional objectives could be added to form a multi-objective model. A multi-objective model allows for a more realistic solution to the routing problem.

Another recommendation for future research involves the roads between the business and the US Highways or interstates. It was assumed in this research that those roads are passable to allow access between the business and the path. Future research should address these secondary roadways and the effects of natural disasters on them.

Although this research only deals with highways, future research is recommended for other modes of freight transportation: waterways, rail and passenger rail. These modes are also important to the economic recovery of an area and an investigation of the relationship between these modes and the highways in the movement of freight after a disaster would be worthwhile.

Summary

Recovery of the transportation network is key to the economic recovery of an area and so a transportation recovery plan is very necessary. This research helps to fill the gap in recovery research and provides a framework for transportation and planning officials to make decisions regarding rebuilding the highway network. The model in this research allows them to start making decisions about the most critical factors in their local area and which roadways should be considered a priority in the reconstruction of the highway network during the recovery phase.

Bibliography

Abbass, Hussein A, Ruhul Sarker, and Charles Newton. *PDE: A Pareto-frontier Differential Evolution Approach for Multi-objective Optimization Problems.* Proceedings of the 2001 Congress on Evolutionary Computation, Canberra ACT, 2600, Australia: School of Computer Science, University of New South Wales, 2001.

Applied Technology Council. *Earthquake Damage Evaluation Data for California.* ATC-13, Redwood City, CA: Applied Technology Council, 1985.

Beasley, David, David R Bull, and Ralph R Martin. *A Sequential Niche Technique for Mulitmodal Function Optimization.* Technical Report No. 93001, UWCC COMMA, 1993.

Berube, Jean-Francois, Michel Gendreau, and Jean-Yves Potvin. "An exact epsilon-constraint method for bi-objective combinatorial optimization problems: Application to the Traveling Salesman Problem with Profits." *European Journal of Operational Research* 194 (2009): 39-50.

Boarnet, Marlon G. *Business Losses, Transportation Damage and the Northridge Earthquake.* Working Paper, Berkeley, CA: The University of California Transportation Center, 1996.

Bolton, Jason. "Top 50 Public Companies." *Memphis Business Journal*, September 19-25, 2008: 19-22.

Bureau, U.S. Census. *2007 Commodity Flow Survey.*2007.www.census.gov(accessed July 2009)

Chang, Stephanie. "Transportation planning for disasters: an accessibility approach." *Environment and Planning A*, 2003: 1051-1072.

Cho, Sungbin, Peter Gordon, James E. Moore II, Harry W. Richardson, Masanobu Shiozuka, and Stephanie Chang. "Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Urban Earthquake." *Journal of Regional Science*, 2001: 39-65.

Coello, Carlos A. "Basic Concepts." Edited by Av.Instituto Politecnico Nacional No. 2508. Mexico: Department of Electrical Engineering.

Commerce, Memphis Regional Chamber of. "Memphis Delivers." *Memphis Delivers.* 2006. http://www.memphisdelivers.com/ (accessed January 5, 2009).

Corporation, GAMS Development. *GAMS.* 2008. http://www.gams.com (accessed May 2009).

Council, Applied Technology. *Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous U.S.* ATC-25, Redwood City, CA: Applied Technology Council, 1991.

Cova, T.J. "GIS in Emergency Management." In *Geographical Information Systems*, by P.A. Longley, M.F. Goodchild, D.J. Maguire and D.W. Rhind, 845-858. New York: John Wiley, 1999.

Cova, Thomas J., and Richard L. Church. "Modelling Community Evacuation Vulnerability using GIS." *International Journal of Geographical Information Science*, 1997: 763-784.

Dhaenens-Flipo, Clarisse. "A bicriteria approach to deal with a constrained single-objective problem." *International Journal of Production Economics*, 2001: 93-101.

ESRI. *ArcGIS: A Complete Integrated System.* 2008. http://www.esri.com/software/arcgis/ (accessed May 2009).

Federal Highway Administration. *The National Highway System.* August 27, 2008. http://www.fhwa.dot.gov/planning/nhs/ (accessed October 10, 2008).

Global Insight. *Memphis Regional Infrastructure Plan.* Report to the Memphis Regional Chamber, Global Insight, 2009.

Guha, Gauri-Shankar. "Estimating Indirect Economic Losses from Electricity Lifeline Disruptions following a Catastrophic Earthquake in Memphis, TN (Using a CGE Model, Survey and Simulations)." *MCEER Student Research Accomplishments.*

Gunes, A. Ertung, and Jacob P. Kovel. "Using GIS in Emergency Management Operations." *Journal of Urban Planning and Development*, September 2000: 136-149.

Ham, Heejoo, Tschangho John Kim, and David Boyce. "Assessment of economic impacts from unexpected events with an interregional commodity flow and multimodal transportation network model." *Science Direct.* August 3, 2004. www.sciencedirect.com (accessed November 6, 2008).

Hillston, Jane. "Model Validation and Verification." *University of Edinburgh School of Informatics.* September 19, 2003.

Hwang, Howard, John B Jernigan, and Yang-Wei Lin. "Evaluation of Seismic Damage to Memphis Bridges and Highway Systems." *Journal of Bridge Engineering*, 2000: 322-330.

ImageCat, Inc. *REDARS.* 2005. http://www.imagecatinc.com/product_redars.html (accessed October 31, 2008).

Jiang, Yi, and Kumares C. Sinha. "Dynamic Optimization Model for Bridge Management Systems." *Transportation Research Record 1211*, 1998: 92-100.

Kovel, Jacob P. "Modeling Disaster Response Planning." *Journal of Urban Planning and Development*, 2000: 26-38.

Laumanns, Marco, Lothar Thiele, and Eckart Zitzler. "An efficient, adaptive parameter variation scheme for metaheuristics based on the epsilon-constraint method." *European Journal of Operational Research* 169 (2006): 932-942.

Lawson, R. Scott, Bouabid Jawhar, and Doug Humphrey. "Predicting Consequences." *Water Environment and Technology*, 2004: 34-38.

National Institute of Building Sciences. *HAZUS: FEMA's Software Program for Estimating Potential Losses from Disasters.* 2008. http://www.fema.gov/plan/prevent/hazus/index.shtm (accessed August 2008).

Nojima, Nobuoto, and Masata Sugito. "Simulation and Evaluation of Post-Earthquake Functional Performance of Transportation Network." *Twelth World Conference on Earthquake Engineering.* Auckland, New Zealand, 2000.

Peeta, Srinivas, and Athanasios K. Ziliaskopoulos. "Foundations of Dynamic Traffic Assignment: The Past, the Present and the Future." *Networks and Spatial Economics*, September 2001: 233-265.

Pradhan, Anu R., Debra F Laefer, and William J Rasdorf. "Infrastructure Management Information System Framework Requirements for Disasters." *Journal of Computing and Civil Engineering*, 2007: 90-101.

Rose, Adam, Juan Benavides, Stephanie E. Chang, Philip Szczesniak, and Dongsoon Lim. "The Regional Economic Impact of an Earthquake: Direct and Indirect Effects of Electricity Lifeline Disruptions." *Journal of Regional Science*, 1997: 437-458.

Rosenthal, Richard E. *GAMS-A Users Guide.* Manual, Washington, D.C.: GAMS Development Corporation, 2008.

Sakakibara, Hiroyuki, Yoshio Kajitani, and Norio Okada. "Road Network Robustness for Avoiding Functional Isolation in Disasters." *Journal of Transportation Engineering*, 2004: 560-567.

Sargent, Robert G. "Verification and Validation of Simulation Models." *Proceedings of the 1998 Winter Simulation Conference.* Washington, D.C.: IEEE, 1998. 121-130.

Sato, Tadanobu, and Koji Ichii. "Optimization of Post-Earthquake Restoration of Lifeline Networks Using Genetic Algorithms." *Proceedings of the Sixth U.S.-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems.* Osaka, Japan: Public Works Research Institute, 1995.

Schweig, Eugene, Joan Gomberg, and James W Hendley II. "Reducing Earthquake Losses Throughout the United States." *United States Geological Survey.* 1995. http://quake.usgs.gov/prepare/factsheets/NewMadrid/ (accessed January 5, 2009).

United States Department of Transportation. *Recovering from Transportation Disasters: The National Transportation Recovery Strategy.* Draft, Office of the Secretary of Transportation, Washington, D.C.: U.S. Department of Transportation, 2009.

Werner, S. D., C.E. Taylor, J.E. Moore, and J.S. Walton. *A Risk Based Methodology for Assessing the Seismic Performance of Highway Systems.* MCEER 00-0014, Buffalo, New York: MCEER University of Buffalo, 2000.

Yan, Shangyao, and Yu-Lin Shih. "Optimal scheduling of emergency roadway repair and subsequent relief distribution." *Computers and Operations Research*, 2008: 2049-2065.

Zielinski, Karin, and Rainer Laur. "Stopping Criteria for a constrained single-objective particle swarm optimization algorithm." *Informatica*, 2007: 51-61.

APPENDIX

Appendix A – Top 25 Revenue Producing Businesses in Shelby County, TN

Company	Local_FTE	2007_FY_Revenue	Latitude	Longitude
FedEx Corp.	32,000	$38 billion	35.04893	-89.96823
Technicolor Video Services, Inc.	2,800	$8.9 billion	35.00604	-89.92639
International Paper Co.	2,300	$22 billion	35.10029	-89.85065
YRC Worldwide, Inc.	1,833	$9.6 billion	35.05959	-90.05196
Smith & Nephew, Inc.	1,815	$3.4 billion	35.06576	-90.01529
Flextronics	1,700	$27.6 billion	35.00572	-89.85061
United Parcel Service, Inc.	1,622	$49.7 billion	35.04826	-89.08642
Medtronic Spinal & Biologics	1,550	$13.5 billion	35.07345	-90.00304
Accredo Health Group, Inc.	1,500	$44.5 billion	35.17044	-89.84592
UTC-Carrier Corp.	1,500	$54.8 billion	35.04203	-89.69232
Nike, Inc.	1,469	$18.6 billion	35.02044	-89.89234
AutoZone, Inc.	1,300	$6.2 billion	35.14201	-90.05575
Jabil Circuit, Inc.	1,200	$12.3 billion	35.01059	-89.88596
Cummins, Inc.	1,100	$13.1 billion	35.03602	-89.87027
Williams-Sonoma, Inc.	1,100	$4 billion	35.58374	-89.91393
Cleo, Inc	1,000	$498.3 million	35.04664	-89.92817
Thomas & Betts Corp.	1,000	$2.1 billion	35.05937	-89.79056
Quebecor World, Inc.	898	$5.7 billion	35.00763	-90.03687
Brother International Corp.	872	$5.7 billion	35.20153	-89.799
Coca-Cola Enterprises, Inc.	800	$28.9 billion	35.03937	-89.92282
Sharp Manuf. Co. of America	700	$34.5 billion	35.03393	-89.88097
Ingram Micro, Inc.	600	$35.1 billion	35.02045	-89.93674
Schering-Plough Corp.	600	$12.7 billion	35.01322	-89.95038
Mueller Industries, Inc.	350	$2.7 billion	35.05613	-89.78345
Buckeye Technologies	319	$825.5 million	35.00743	-89.95113
GTx, Inc.	138	$7.1 million	35.00725	-90.0335
Verso Paper Corp.	85	$1.6 billion	35.05877	-89.83726

Source: Memphis Business Journal, September 19-25, 2008, pgs. 21-22.

Appendix B – Bridge Information for Shelby County Scenarios

Shelby County Demonstration A

Bridge #	Damage Level	Replace Cost($)	Repair Cost($)	Time(days)
0	slight	1107691.2	33230.736	21
1	slight	2029341.6	507335.4	19
2	complete	930204	930204	153
3	moderate	2619540	1309770	25
4	moderate	3261060	1630530	27
5	extensive	2611414.1	1958560.58	44
6	complete	2702509.9	2702509.9	105
7	extensive	4105870.6	3079402.95	62
8	moderate	1707583.7	853791.85	14
9	none	754427.5	0	2
10	none	2951847.4	0	1
11	slight	2095632	523908	21
12	extensive	648648	486486	51
13	slight	3795232.3	948808.08	17
14	complete	2619540	2619540	194
15	extensive	1852139.5	1389104.63	38
16	none	1481911.2	0	3
17	complete	2101334.4	2101334.4	287
18	complete	2792465.3	2792465.3	287
19	moderate	1596672	798336	18
20	slight	1227441.6	306860.4	18
21	moderate	1766318.4	883159.2	17
22	slight	2316600	579150	21
23	complete	3600210.2	3600210.2	184
24	moderate	1304424	652212	20
25	complete	492972.5	492972.5	170
26	slight	2119582.1	529895.53	14
27	moderate	1122660	561330	26
28	extensive	1368576	1026432	68
29	extensive	3155423	2366567.25	84
30	complete	1240842.2	1240842.2	179
31	complete	1847292.5	1847292.5	149
32	complete	958858.6	958858.6	204
33	moderate	1204632	602316	23

34	moderate	1547916.5	773958.25	17
35	extensive	364240.8	273180.6	69
36	extensive	111110693.8	83333020.35	57
37	extensive	894136.3	670602.23	42
38	complete	3947486.4	3947486.4	171
39	complete	2408693.8	2408693.8	280
40	complete	2408693.8	2408693.8	154
41	moderate	1212472.8	606236.4	18
42	none	1212472.8	0	2
43	extensive	1005903.4	754427.55	35
44	slight	1925985.6	481496.4	14
45	slight	2720757.6	680189.4	20
46	extensive	1780859.5	1335644.63	68
47	none	2226074.4	0	1
48	complete	1335644.6	1335644.6	202
49	extensive	8119077.1	6089307.83	84
50	none	7378050.2	0	5
51	complete	1604655.4	1604655.4	259
52	complete	1965332.2	1965332.2	295
53	moderate	1184245.9	592122.95	24
54	extensive	1184245.9	888184.43	30
55	extensive	1347192	1010394	84
56	moderate	1347192	673596	20
57	none	1548629.3	0	1
58	extensive	1548629.3	1161471.98	67
59	moderate	7378050.2	3689025.1	26
60	complete	6170139.4	6170139.4	144
61	moderate	3944777.8	1972388.9	14
62	moderate	3616034.4	1808017.2	17
63	moderate	5161527.4	2580763.7	24
64	extensive	2460728.2	1845546.15	46
65	complete	1461382.6	1461382.6	181
66	none	1576000.8	0	4
67	none	991647.4	0	5
68	extensive	1149889	862416.75	66
69	slight	22070854.1	5517713.53	18
70	extensive	4148496	3111372	77
71	complete	1877515.2	1877515.2	90
72	slight	4663422.7	1165855.68	14
73	complete	2628521.3	2628521.3	128
74	slight	6241276.8	1560319.2	20

75	extensive	775526.4	581644.8	49
76	none	775526.4	0	4
77	extensive	814302.7	610727.03	39
78	extensive	1335217	1001412.75	64
79	complete	2359938.2	2359938.2	289
80	none	1184388.5	0	4
81	extensive	581644.8	290822.4	59
82	slight	581644.8	145411.2	20
83	extensive	772817.8	386408.9	46
84	extensive	772817.8	579613.35	42
85	complete	730334.9	730334.9	297
86	extensive	730334.9	547751.18	80
87	extensive	1553904	1165428	68
88	moderate	1600521.1	800260.55	24
89	none	2085082.6	0	4
90	moderate	5227105	2613552.5	20
91	slight	5065441.9	1266360.48	18
92	extensive	772817.8	579613.35	69
93	slight	1781429.8	445357.45	17
94	slight	1429876.8	357469.2	15
95	complete	640807.2	640807.2	150
96	none	738033.1	0	2
97	extensive	3286720.8	2465040.6	44
98	slight	3286720.8	821680.2	19
99	extensive	1801388.2	1351041.15	49
100	slight	1017878.4	254469.6	21
101	complete	1017878.4	1017878.4	92
102	moderate	1280046.2	640023.1	22
103	complete	1477777	1477777	211
104	none	838252.8	0	3
105	extensive	996066.7	747050.03	71
106	moderate	1032419.5	516209.75	25
107	moderate	545719.7	272859.85	14
108	slight	1272348	318087	17
109	moderate	586777	293388.5	18
110	none	2574633.6	0	3
111	extensive	754427.5	565820.63	67
112	none	1917717.1	0	5
113	moderate	1334361.6	667180.8	27
114	moderate	1334361.6	667180.8	16
115	none	593762.4	0	3

116	slight	2371057.9	592764.48	17
117	extensive	1776582.7	1332437.03	79
118	slight	1862546.4	465636.6	15
119	moderate	1094860.8	547430.4	15
120	complete	1094860.8	1094860.8	95
121	extensive	3700144.8	2775108.6	31
122	none	3700144.8	0	2
123	complete	1066348.8	1066348.8	119
124	moderate	1066348.8	533174.4	25
125	complete	1020729.6	1020729.6	268
126	slight	826848	206712	21
127	moderate	1054231.2	527115.6	20
128	extensive	1301430.2	976072.65	28
129	none	928350.7	0	5
130	none	928350.7	0	3
131	complete	827988.5	827988.5	145
132	slight	827988.5	206997.13	16
133	complete	953441.3	953441.3	125
134	slight	680438.9	170109.73	17
135	complete	0	0	113
136	moderate	1581275.5	790637.75	17
137	extensive	2031194.9	1523396.18	76
138	complete	1580705.3	1580705.3	217
139	extensive	1850428.8	1387821.6	65
140	complete	1643431.7	1643431.7	93
141	complete	5250199.7	5250199.7	155
142	moderate	1817640	908820	14
143	extensive	1662534.7	1246901.03	47
144	slight	3853681.9	963420.48	15
145	none	1424174.4	0	2
146	none	857070.7	0	3
147	slight	2340265	585066.25	16
148	complete	3284582.4	3284582.4	101
149	moderate	2856047	1428023.5	19
150	slight	10538035.2	2634508.8	17
151	none	538306.6	0	3
152	extensive	439084.8	329313.6	39
153	slight	6246694.1	1561673.53	20
154	complete	1719273.6	1719273.6	282
155	slight	337011.8	84252.95	17
156	moderate	381205.4	190602.7	20

157	none	299518.6	0	2
158	complete	1089158.4	1089158.4	225
159	moderate	707953	353976.5	24
160	slight	733471.2	183367.8	21
161	complete	748440	748440	159
162	complete	90810.7	90810.7	187
163	moderate	119750.4	59875.2	27
164	moderate	1167566.4	583783.2	25
165	moderate	3113510.4	1556755.2	23
166	moderate	395746.6	197873.3	20
167	none	2489953	0	1
168	none	869616	0	3
169	complete	5816448	5816448	175
170	moderate	1186099.2	593049.6	18
171	moderate	336156.5	168078.25	25
172	moderate	317481.1	158740.55	23
173	extensive	3171104.6	2378328.45	66
174	complete	3152001.6	3152001.6	279
175	extensive	1910304	1432728	40
176	none	1910304	0	2
177	extensive	778377.6	583783.2	81
178	slight	1299006.7	324751.68	17
179	complete	1146182.4	1146182.4	141
180	extensive	668606.4	501454.8	36
181	extensive	601318.1	450988.58	47
182	extensive	1596672	1197504	64
183	moderate	1661964.5	830982.25	17
184	complete	1661964.5	1661964.5	205
185	moderate	3720816	1860408	18
186	moderate	730477.4	365238.7	21
187	moderate	1538222.4	769111.2	20
188	slight	842387	210596.75	14
189	complete	4886529.1	4886529.1	130
190	extensive	5474304	4105728	50
191	moderate	2422379.5	1211189.75	14
192	complete	1886068.8	1886068.8	265
193	none	935193.6	0	1
194	complete	5223398.4	5223398.4	115
195	extensive	2874009.6	2155507.2	84
196	moderate	1626894.7	813447.35	17
197	none	1146182.4	0	3

198	moderate	1317254.4	658627.2	26
199	complete	23648708.2	23648708.2	95
200	extensive	489265.9	366949.43	30
201	complete	16286339.5	16286339.5	174
202	moderate	472158.7	236079.35	24
203	none	670032	0	3
204	slight	2046448.8	511612.2	20
205	complete	1042541.3	1042541.3	189
206	moderate	1919998.1	959999.05	27
207	slight	898698.2	224674.55	16
208	none	170644.3	0	4
209	slight	1661536.8	415384.2	21
210	moderate	2823115.7	1411557.85	17
211	slight	1543924.8	385981.2	16
212	none	3452660.6	0	1
213	extensive	5295961.4	3971971.05	58
214	slight	1820206.1	455051.53	21
215	extensive	1216321.9	912241.43	46
216	none	991932.5	0	1
217	slight	1945944	486486	14

Shelby County Demonstration B

Bridge #	Damage Level	Replace Cost($)	Repair Cost($)	Time(days)
0	moderate	1107691.2	88615.30	27
1	moderate	2029341.6	162347.33	15
2	complete	930204	930204.00	94
3	extensive	2619540	654885.00	80
4	extensive	3261060	815265.00	44
5	complete	2611414.1	2611414.10	125
6	complete	2702509.9	2702509.90	225
7	complete	4105870.6	4105870.60	288
8	extensive	1707583.7	426895.93	28
9	slight	754427.5	22632.83	21
10	slight	2951847.4	88555.42	19
11	moderate	2095632	167650.56	22
12	complete	648648	648648.00	204
13	moderate	3795232.3	303618.58	25
14	complete	2619540	2619540.00	201

15	complete	1852139.5	1852139.50	273
16	slight	1481911.2	44457.34	20
17	complete	2101334.4	2101334.40	94
18	complete	2792465.3	2792465.30	98
19	extensive	1596672	399168.00	76
20	moderate	1227441.6	98195.33	19
21	extensive	1766318.4	441579.60	76
22	moderate	2316600	185328.00	15
23	complete	3600210.2	3600210.20	236
24	extensive	1304424	326106.00	65
25	complete	492972.5	492972.50	103
26	moderate	2119582.1	169566.57	27
27	extensive	1122660	280665.00	53
28	complete	1368576	1368576.00	266
29	complete	3155423	3155423.00	291
30	complete	1240842.2	1240842.20	112
31	complete	1847292.5	1847292.50	291
32	complete	958858.6	958858.60	187
33	extensive	1204632	301158.00	54
34	extensive	1547916.5	386979.13	71
35	complete	364240.8	364240.80	187
36	complete	111110693.8	111110693.80	158
37	complete	894136.3	894136.30	121
38	complete	3947486.4	3947486.40	138
39	complete	2408693.8	2408693.80	156
40	complete	2408693.8	2408693.80	202
41	extensive	1212472.8	303118.20	68
42	slight	1212472.8	36374.18	15
43	complete	1005903.4	1005903.40	228
44	moderate	1925985.6	154078.85	24
45	moderate	2720757.6	217660.61	18
46	complete	1780859.5	1780859.50	122
47	slight	2226074.4	66782.23	19
48	complete	1335644.6	1335644.60	257
49	complete	8119077.1	8119077.10	116
50	slight	7378050.2	221341.51	17
51	complete	1604655.4	1604655.40	117
52	complete	1965332.2	1965332.20	286
53	extensive	1184245.9	296061.48	65
54	complete	1184245.9	1184245.90	122
55	complete	1347192	1347192.00	228

56	extensive	1347192	336798.00	30
57	slight	1548629.3	46458.88	21
58	complete	1548629.3	1548629.30	147
59	extensive	7378050.2	1844512.55	52
60	complete	6170139.4	6170139.40	224
61	extensive	3944777.8	986194.45	84
62	extensive	3616034.4	904008.60	29
63	extensive	5161527.4	1290381.85	46
64	complete	2460728.2	2460728.20	272
65	complete	1461382.6	1461382.60	287
66	slight	1576000.8	47280.02	17
67	slight	991647.4	29749.42	14
68	complete	1149889	1149889.00	91
69	moderate	22070854.1	1765668.33	15
70	complete	4148496	4148496.00	95
71	complete	1877515.2	1877515.20	294
72	moderate	4663422.7	373073.82	22
73	complete	2628521.3	2628521.30	194
74	moderate	6241276.8	499302.14	24
75	complete	775526.4	775526.40	129
76	slight	775526.4	23265.79	15
77	complete	814302.7	814302.70	97
78	complete	1335217	1335217.00	219
79	complete	2359938.2	2359938.20	118
80	slight	1184388.5	35531.66	18
81	complete	581644.8	581644.80	119
82	moderate	581644.8	46531.58	26
83	complete	772817.8	772817.80	179
84	complete	772817.8	772817.80	101
85	complete	730334.9	730334.90	288
86	complete	730334.9	730334.90	148
87	complete	1553904	1553904.00	297
88	extensive	1600521.1	400130.28	46
89	slight	2085082.6	62552.48	17
90	extensive	5227105	1306776.25	63
91	moderate	5065441.9	405235.35	21
92	complete	772817.8	772817.80	284
93	moderate	1781429.8	142514.38	23
94	moderate	1429876.8	114390.14	24
95	complete	640807.2	640807.20	187
96	slight	738033.1	22140.99	18

97	complete	3286720.8	3286720.80	284
98	moderate	3286720.8	262937.66	17
99	complete	1801388.2	1801388.20	118
100	moderate	1017878.4	81430.27	26
101	complete	1017878.4	1017878.40	145
102	extensive	1280046.2	320011.55	56
103	complete	1477777	1477777.00	185
104	slight	838252.8	25147.58	21
105	complete	996066.7	996066.70	269
106	extensive	1032419.5	258104.88	64
107	extensive	545719.7	136429.93	33
108	moderate	1272348	101787.84	20
109	extensive	586777	146694.25	64
110	slight	2574633.6	77239.01	14
111	complete	754427.5	754427.50	140
112	slight	1917717.1	57531.51	19
113	extensive	1334361.6	333590.40	48
114	extensive	1334361.6	333590.40	60
115	slight	593762.4	17812.87	15
116	moderate	2371057.9	189684.63	14
117	complete	1776582.7	1776582.70	136
118	moderate	1862546.4	149003.71	16
119	extensive	1094860.8	273715.20	32
120	extensive	1094860.8	273715.20	50
121	complete	3700144.8	3700144.80	293
122	slight	3700144.8	111004.34	20
123	complete	1066348.8	1066348.80	236
124	extensive	1066348.8	266587.20	42
125	complete	1020729.6	1020729.60	236
126	moderate	826848	66147.84	15
127	extensive	1054231.2	263557.80	36
128	complete	1301430.2	1301430.20	201
129	slight	928350.7	27850.52	14
130	slight	928350.7	27850.52	18
131	complete	827988.5	827988.50	255
132	moderate	827988.5	66239.08	18
133	complete	953441.3	953441.30	111
134	moderate	680438.9	54435.11	17
135	complete	0	0.00	172
136	extensive	1581275.5	395318.88	79
137	complete	2031194.9	2031194.90	187

138	complete	1580705.3	1580705.30	218
139	complete	1850428.8	1850428.80	261
140	complete	1643431.7	1643431.70	270
141	complete	5250199.7	5250199.70	223
142	extensive	1817640	454410.00	81
143	complete	1662534.7	1662534.70	133
144	moderate	3853681.9	308294.55	17
145	slight	1424174.4	42725.23	16
146	slight	857070.7	25712.12	18
147	moderate	2340265	187221.20	18
148	complete	3284582.4	3284582.40	160
149	extensive	2856047	714011.75	74
150	moderate	10538035.2	843042.82	15
151	slight	538306.6	16149.20	14
152	complete	439084.8	439084.80	163
153	moderate	6246694.1	499735.53	17
154	complete	1719273.6	1719273.60	279
155	moderate	337011.8	26960.94	26
156	extensive	381205.4	95301.35	82
157	slight	299518.6	8985.56	17
158	complete	1089158.4	1089158.40	193
159	extensive	707953	176988.25	49
160	moderate	733471.2	58677.70	18
161	complete	748440	748440.00	243
162	complete	90810.7	90810.70	175
163	extensive	119750.4	29937.60	30
164	extensive	1167566.4	291891.60	74
165	extensive	3113510.4	778377.60	61
166	extensive	395746.6	98936.65	54
167	slight	2489953	74698.59	21
168	slight	869616	26088.48	19
169	complete	5816448	5816448.00	107
170	extensive	1186099.2	296524.80	68
171	extensive	336156.5	84039.13	46
172	extensive	317481.1	79370.28	80
173	complete	3171104.6	3171104.60	233
174	complete	3152001.6	3152001.60	138
175	complete	1910304	1910304.00	210
176	slight	1910304	57309.12	14
177	complete	778377.6	778377.60	224
178	moderate	1299006.7	103920.54	22

179	complete	1146182.4	1146182.40	105
180	complete	668606.4	668606.40	234
181	complete	601318.1	601318.10	211
182	complete	1596672	1596672.00	130
183	extensive	1661964.5	415491.13	44
184	complete	1661964.5	1661964.50	225
185	extensive	3720816	930204.00	40
186	extensive	730477.4	182619.35	78
187	extensive	1538222.4	384555.60	76
188	moderate	842387	67390.96	24
189	complete	4886529.1	4886529.10	298
190	complete	5474304	5474304.00	295
191	extensive	2422379.5	605594.88	62
192	complete	1886068.8	1886068.80	109
193	slight	935193.6	28055.81	21
194	complete	5223398.4	5223398.40	207
195	complete	2874009.6	2874009.60	274
196	extensive	1626894.7	406723.68	36
197	slight	1146182.4	34385.47	17
198	extensive	1317254.4	329313.60	59
199	complete	23648708.2	23648708.20	219
200	complete	489265.9	489265.90	208
201	complete	16286339.5	16286339.50	262
202	extensive	472158.7	118039.68	63
203	slight	670032	20100.96	14
204	moderate	2046448.8	163715.90	16
205	complete	1042541.3	1042541.30	296
206	extensive	1919998.1	479999.53	41
207	moderate	898698.2	71895.86	22
208	slight	170644.3	5119.33	17
209	slight	1661536.8	49846.10	14
210	extensive	2823115.7	705778.93	55
211	moderate	1543924.8	123513.98	15
212	slight	3452660.6	103579.82	14
213	complete	5295961.4	5295961.40	122
214	moderate	1820206.1	145616.49	27
215	complete	1216321.9	1216321.90	298
216	slight	991932.5	29757.98	16
217	moderate	1945944	155675.52	24

Appendix C – Hypothetical Network Bridge Data

(Time is in Days and Cost is in Dollars)

ID_No	COST	Damage_Level	Repair_Cost	TotalCost	Repair_Time
1	$1,107.69	slight	277		30
2	$2,029.34	complete	2029		120
3	$930.20	moderate	465		60
4	$3,261.06	none	500		10
5	$2,611.41	complete	2611	5383	120
6	$2,702.51	slight	676		30
7	$4,105.87	none	500		10
8	$1,707.58	moderate	854		60
9	$754.43	none	500		10
10	$2,951.85	none	500	1529	10
11	$2,095.63	slight	524		30
12	$648.65	slight	162		30
13	$3,795.23	complete	3795		120
14	$2,619.54	none	500		10
15	$1,852.14	slight	463	4944	30
16	$1,481.91	moderate	741		60
17	$2,101.33	moderate	1051		60
18	$2,792.47	complete	2792		120
19	$1,596.67	complete	1597		120
20	$1,227.44	slight	307	6488	30
21	$1,766.32	none	500		10
22	$2,316.60	slight	579		30
23	$3,600.21	slight	900		30
24	$1,304.42	moderate	652		60
25	$492.97	extensive	370	2501	90
26	$2,119.58	extensive	1590		90
27	$1,122.66	moderate	561		60
28	$1,368.58	moderate	684		60
29	$3,155.42	none	500		10
30	$1,240.84	complete	1241	4076	120
31	$1,847.29	slight	462		30
32	$958.86	slight	240		30
33	$1,204.63	moderate	602		60
34	$1,547.92	slight	387		30

35	$364.24	moderate	182	1873	60
36	$111,110.69	slight	27778		30
37	$894.14	complete	894		120
38	$3,947.49	complete	3947		120
39	$2,408.69	moderate	1204		60
40	$2,408.69	moderate	1204	35028	60
41	$1,212.47	none	500		10
42	$1,212.47	moderate	606		60
43	$1,005.90	extensive	754		90
44	$1,925.99	none	500		10
45	$2,720.76	none	500	1361	10
46	$1,780.86	slight	445		30
47	$2,226.07	complete	2226		120
48	$1,335.64	slight	334		30
49	$8,119.08	slight	2030		30
50	$7,378.05	extensive	5534	10569	90
51	$1,604.66	extensive	1203		90
52	$1,965.33	moderate	983		60
53	$1,184.25	moderate	592		60
54	$1,184.25	none	500		10
55	$1,347.19	none	500	2778	10
56	$1,347.19	complete	1347		120
57	$1,548.63	complete	1549		120
58	$1,548.63	none	500		10
59	$7,378.05	slight	1845		30
60	$6,170.14	slight	1543	6283	30
61	$3,944.78	none	500		10
62	$3,616.03	none	500		10
63	$5,161.53	moderate	2581		60
64	$2,460.73	none	500		10
65	$1,461.38	none	500	2581	10
66	$1,576.00	extensive	1182		90
67	$991.65	none	500		10
68	$1,149.89	none	500		10
69	$22,070.85	complete	22071		120
70	$4,148.50	moderate	2074	25327	60
71	$1,877.52	extensive	1408		90
72	$4,663.42	none	500		10
73	$2,628.52	complete	2629		120
74	$6,241.28	moderate	3121		60
75	$775.53	moderate	388	7545	60

76	$775.53	moderate	388		60
77	$814.30	moderate	407		60
78	$1,335.22	none	500		10
79	$2,359.94	extensive	1770		90
80	$1,184.39	slight	296	2861	30
81	$581.64	none	500		10
82	$581.64	extensive	436		90
83	$772.82	complete	773		120
84	$772.82	moderate	386		60
85	$730.33	extensive	548	2143	90
86	$730.33	slight	183		30
87	$1,553.90	moderate	777		60
88	$1,600.52	extensive	1200		90
89	$2,085.08	complete	2085		120
90	$5,227.11	complete	5227	9472	120
91	$5,065.44	extensive	3799		90
92	$772.82	complete	773		120
93	$1,781.43	slight	445		30
94	$1,429.88	complete	1430		120
95	$640.81	moderate	320	6768	60
96	$738.03	complete	738		120
97	$3,286.72	none	500		10
98	$3,286.72	extensive	2465		90
99	$1,801.39	none	500		10
100	$1,017.88	moderate	509	3712	60

Appendix D - Sensitivity Analysis Data

(Time is in Days)

Bridge #	COST ($)	TIME_1	TIME_2	TIME_3	TIME_4	TIME_5
0	33230.74	21	23	25	28	31
1	507335.4	19	21	23	25	28
2	930204	153	168	185	204	224
3	1309770	25	28	30	33	37
4	1630530	27	30	33	36	40
5	1958561	44	48	53	59	64
6	2702510	105	116	127	140	154
7	3079403	62	68	75	83	91
8	853791.9	14	15	17	19	20
9	0	2	2	2	3	3
10	0	1	1	1	1	1
11	523908	21	23	25	28	31
12	486486	51	56	62	68	75
13	948808.1	17	19	21	23	25
14	2619540	194	213	235	258	284
15	1389105	38	42	46	51	56
16	0	3	3	4	4	4
17	2101334	287	316	347	382	420
18	2792465	287	316	347	382	420
19	798336	18	20	22	24	26
20	306860.4	18	20	22	24	26
21	883159.2	17	19	21	23	25
22	579150	21	23	25	28	31
23	3600210	184	202	223	245	269
24	652212	20	22	24	27	29
25	492972.5	170	187	206	226	249
26	529895.5	14	15	17	19	20
27	561330	26	29	31	35	38
28	1026432	68	75	82	91	100
29	2366567	84	92	102	112	123
30	1240842	179	197	217	238	262
31	1847293	149	164	180	198	218
32	958858.6	204	224	247	272	299
33	602316	23	25	28	31	34

34	773958.3	17	19	21	23	25
35	273180.6	69	76	83	92	101
36	83333020	57	63	69	76	83
37	670602.2	42	46	51	56	61
38	3947486	171	188	207	228	250
39	2408694	280	308	339	373	410
40	2408694	154	169	186	205	225
41	606236.4	18	20	22	24	26
42	0	2	2	2	3	3
43	754427.6	35	39	42	47	51
44	481496.4	14	15	17	19	20
45	680189.4	20	22	24	27	29
46	1335645	68	75	82	91	100
47	0	1	1	1	1	1
48	1335645	202	222	244	269	296
49	6089308	84	92	102	112	123
50	0	5	6	6	7	7
51	1604655	259	285	313	345	379
52	1965332	295	325	357	393	432
53	592123	24	26	29	32	35
54	888184.4	30	33	36	40	44
55	1010394	84	92	102	112	123
56	673596	20	22	24	27	29
57	0	1	1	1	1	1
58	1161472	67	74	81	89	98
59	3689025	26	29	31	35	38
60	6170139	144	158	174	192	211
61	1972389	14	15	17	19	20
62	1808017	17	19	21	23	25
63	2580764	24	26	29	32	35
64	1845546	46	51	56	61	67
65	1461383	181	199	219	241	265
66	0	4	4	5	5	6
67	0	5	6	6	7	7
68	862416.8	66	73	80	88	97
69	5517714	18	20	22	24	26
70	3111372	77	85	93	102	113
71	1877515	90	99	109	120	132
72	1165856	14	15	17	19	20
73	2628521	128	141	155	170	187
74	1560319	20	22	24	27	29

75	581644.8	49	54	59	65	72
76	0	4	4	5	5	6
77	610727	39	43	47	52	57
78	1001413	64	70	77	85	94
79	2359938	289	318	350	385	423
80	0	4	4	5	5	6
81	290822.4	59	65	71	79	86
82	145411.2	20	22	24	27	29
83	386408.9	46	51	56	61	67
84	579613.4	42	46	51	56	61
85	730334.9	297	327	359	395	435
86	547751.2	80	88	97	106	117
87	1165428	68	75	82	91	100
88	800260.6	24	26	29	32	35
89	0	4	4	5	5	6
90	2613553	20	22	24	27	29
91	1266360	18	20	22	24	26
92	579613.4	69	76	83	92	101
93	445357.5	17	19	21	23	25
94	357469.2	15	17	18	20	22
95	640807.2	150	165	182	200	220
96	0	2	2	2	3	3
97	2465041	44	48	53	59	64
98	821680.2	19	21	23	25	28
99	1351041	49	54	59	65	72
100	254469.6	21	23	25	28	31
101	1017878	92	101	111	122	135
102	640023.1	22	24	27	29	32
103	1477777	211	232	255	281	309
104	0	3	3	4	4	4
105	747050	71	78	86	95	104
106	516209.8	25	28	30	33	37
107	272859.9	14	15	17	19	20
108	318087	17	19	21	23	25
109	293388.5	18	20	22	24	26
110	0	3	3	4	4	4
111	565820.6	67	74	81	89	98
112	0	5	6	6	7	7
113	667180.8	27	30	33	36	40
114	667180.8	16	18	19	21	23
115	0	3	3	4	4	4

116	592764.5	17	19	21	23	25
117	1332437	79	87	96	105	116
118	465636.6	15	17	18	20	22
119	547430.4	15	17	18	20	22
120	1094861	95	105	115	126	139
121	2775109	31	34	38	41	45
122	0	2	2	2	3	3
123	1066349	119	131	144	158	174
124	533174.4	25	28	30	33	37
125	1020730	268	295	324	357	392
126	206712	21	23	25	28	31
127	527115.6	20	22	24	27	29
128	976072.7	28	31	34	37	41
129	0	5	6	6	7	7
130	0	3	3	4	4	4
131	827988.5	145	160	175	193	212
132	206997.1	16	18	19	21	23
133	953441.3	125	138	151	166	183
134	170109.7	17	19	21	23	25
135	0	113	124	137	150	165
136	790637.8	17	19	21	23	25
137	1523396	76	84	92	101	111
138	1580705	217	239	263	289	318
139	1387822	65	72	79	87	95
140	1643432	93	102	113	124	136
141	5250200	155	171	188	206	227
142	908820	14	15	17	19	20
143	1246901	47	52	57	63	69
144	963420.5	15	17	18	20	22
145	0	2	2	2	3	3
146	0	3	3	4	4	4
147	585066.3	16	18	19	21	23
148	3284582	101	111	122	134	148
149	1428024	19	21	23	25	28
150	2634509	17	19	21	23	25
151	0	3	3	4	4	4
152	329313.6	39	43	47	52	57
153	1561674	20	22	24	27	29
154	1719274	282	310	341	375	413
155	84252.95	17	19	21	23	25
156	190602.7	20	22	24	27	29

157	0	2	2	2	3	3
158	1089158	225	248	272	299	329
159	353976.5	24	26	29	32	35
160	183367.8	21	23	25	28	31
161	748440	159	175	192	212	233
162	90810.7	187	206	226	249	274
163	59875.2	27	30	33	36	40
164	583783.2	25	28	30	33	37
165	1556755	23	25	28	31	34
166	197873.3	20	22	24	27	29
167	0	1	1	1	1	1
168	0	3	3	4	4	4
169	5816448	175	193	212	233	256
170	593049.6	18	20	22	24	26
171	168078.3	25	28	30	33	37
172	158740.6	23	25	28	31	34
173	2378328	66	73	80	88	97
174	3152002	279	307	338	371	408
175	1432728	40	44	48	53	59
176	0	2	2	2	3	3
177	583783.2	81	89	98	108	119
178	324751.7	17	19	21	23	25
179	1146182	141	155	171	188	206
180	501454.8	36	40	44	48	53
181	450988.6	47	52	57	63	69
182	1197504	64	70	77	85	94
183	830982.3	17	19	21	23	25
184	1661965	205	226	248	273	300
185	1860408	18	20	22	24	26
186	365238.7	21	23	25	28	31
187	769111.2	20	22	24	27	29
188	210596.8	14	15	17	19	20
189	4886529	130	143	157	173	190
190	4105728	50	55	61	67	73
191	1211190	14	15	17	19	20
192	1886069	265	292	321	353	388
193	0	1	1	1	1	1
194	5223398	115	127	139	153	168
195	2155507	84	92	102	112	123
196	813447.4	17	19	21	23	25
197	0	3	3	4	4	4

198	658627.2	26	29	31	35	38
199	23648708	95	105	115	126	139
200	366949.4	30	33	36	40	44
201	16286340	174	191	211	232	255
202	236079.4	24	26	29	32	35
203	0	3	3	4	4	4
204	511612.2	20	22	24	27	29
205	1042541	189	208	229	252	277
206	959999.1	27	30	33	36	40
207	224674.6	16	18	19	21	23
208	0	4	4	5	5	6
209	415384.2	21	23	25	28	31
210	1411558	17	19	21	23	25
211	385981.2	16	18	19	21	23
212	0	1	1	1	1	1
213	3971971	58	64	70	77	85
214	455051.5	21	23	25	28	31
215	912241.4	46	51	56	61	67
216	0	1	1	1	1	1
217	486486	14	15	17	19	20