Earthquake Loss Estimation Including Transportation Network Damage

by

Umang Gupta

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Author . . . .
Department of Civil and Environmental Engineering
June 15, 2001

Certified by . . . .
Joseph M. Sussman
JR East Professor
Thesis Supervisor

Certified by . . . .
Daniele Veneziano
Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by . . . .
Oral Buyukozturk
Chairman, Departmental Committee on Graduate Studies

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Abstract

Large earthquakes have the potential of causing extensive damage and enormous economic losses. These losses are primarily attributable to the reduction in functionality of various facilities in the affected region and the rebuilding costs, and can be reduced through strategic pre- and post-earthquake decisions.

This thesis describes an integrated methodology to estimate losses due to scenario earthquakes, with emphasis on the reduced functionality of the transportation infrastructure. The methodology integrates variables that were previously considered exogenous to the transportation system, through models for reduced industrial production capacity, and damage to lifelines, residential clusters and other structural components in an integrated framework. By modifying input parameters, one can evaluate the effect on the losses of various mitigating actions. The methodology is thus useful for prioritizing retrofitting efforts and in general for developing pre and post- earthquake strategies for lowering economic losses.

A case study of a New Madrid scenario earthquake is presented. Future efforts needed to improve the loss estimation capability of this methodology are identified.

Thesis Supervisor: Dr. Joseph M. Sussman
Title: JR East Professor

Thesis Supervisor: Dr. Daniele Veneziano
Title: Professor of Civil and Environmental Engineering

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Chapter 1

Introduction

Large earthquakes have the potential of causing extensive damage and enormous economic losses. There are three basic components of this economic loss: direct losses that reflect the damage to the physical infrastructure; business interruption or indirect losses from the effects of the reduced functionality of lifelines on economic sectors and dislocations in the economic framework; and induced losses, which are caused by collateral hazards such as fire, flooding, debris, and hazardous chemical releases[1]. Of these, direct and induced economic losses are limited to the affected region, whereas the indirect economic losses can spread over a large geographical area as spatially distributed industries interact and depend on each other.

Indirect losses arise through a complex system of linkages in the economic framework. Industries depend on other industries, governments and people to buy their products, other industrial sectors for inputs, lifelines[2] to support production activities, infrastructure (building stock, machinery, etc.), and the human resource. An earthquake event that limits the functionality of any of the elements of this network is bound to create a general disorder in the economic framework, not limited to that

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[1] Researchers have used various classification systems for economic losses. This classification is closest to Applied Technology Council's ATC-25 (Applied Technology Council (ATC), 1991) system of direct, indirect and secondary losses. Direct losses in this thesis correspond to the direct losses in ATC-25; the indirect losses are a combination of the indirect (effects of lifelines) and secondary (due to industry interaction) losses in ATC-25

[2] Lifelines include electric-power distribution networks, oil and gas networks, transportation infrastructure, water pipeline networks, etc.

particular element. None of these elements can thus be isolated from the rest of the system for a complete loss analysis.

The transportation lifeline is an inseparable part of this framework and damage to parts of this system can lead to consequences throughout the regional economy. For example, an industry might not be able to source essential inputs to produce their products because of problems in transporting commodities, or its employees might not have access to the workplace, thus lowering overall productivity.

The U.S. Gross Domestic Product (GDP) was over $6 trillion in 1992. $728 billion, or 12.1% of this GDP, were attributable to transportation-related activities (Central U.S. Earthquake Consortium, 2000). This dependence implies that damage to the transportation infrastructure has the potential of causing widespread indirect economic losses. These transportation-related losses are mainly attributable to access problems and delays to freight flows, commuters and customers in the post-earthquake scenario.

Research on past earthquakes also suggests that transportation network damage is responsible for substantial indirect losses. The 1994 Northridge earthquake[3] resulted in heavy damage to the transportation network. Approximately $1.5 billion, or 23% of all indirect losses were attributable to the transportation network damage (Shinozuka et al., 1998).The losses are sizeable, though modest in comparison to the total direct loss of over $25 billion. It must however be noted here that the transportation-related losses due to the the Northridge earthquake were ameliorated by the substantial redundancy in the L.A. highway system (Gordon et al., 1998). A similar earthquake in Central U.S. can possibly have much severer consequences (Central U.S. Earthquake Consortium, 2000) because of the low network redundancy and inadequate seismic design criteria of bridges in that region. The Federal Emergency Management Agency (FEMA) loss estimation study concluded that a 7.6 magnitude New Madrid earthquake will cause major to destructive damage to almost all of the bridges and overpasses in the city of Memphis and Shelby County (FEMA, 1985).

Moreover, transportation systems take substantially longer to restore when com-

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[3] A 6.8 magnitude earthquake that shook Los Angeles on January 17, 1994.

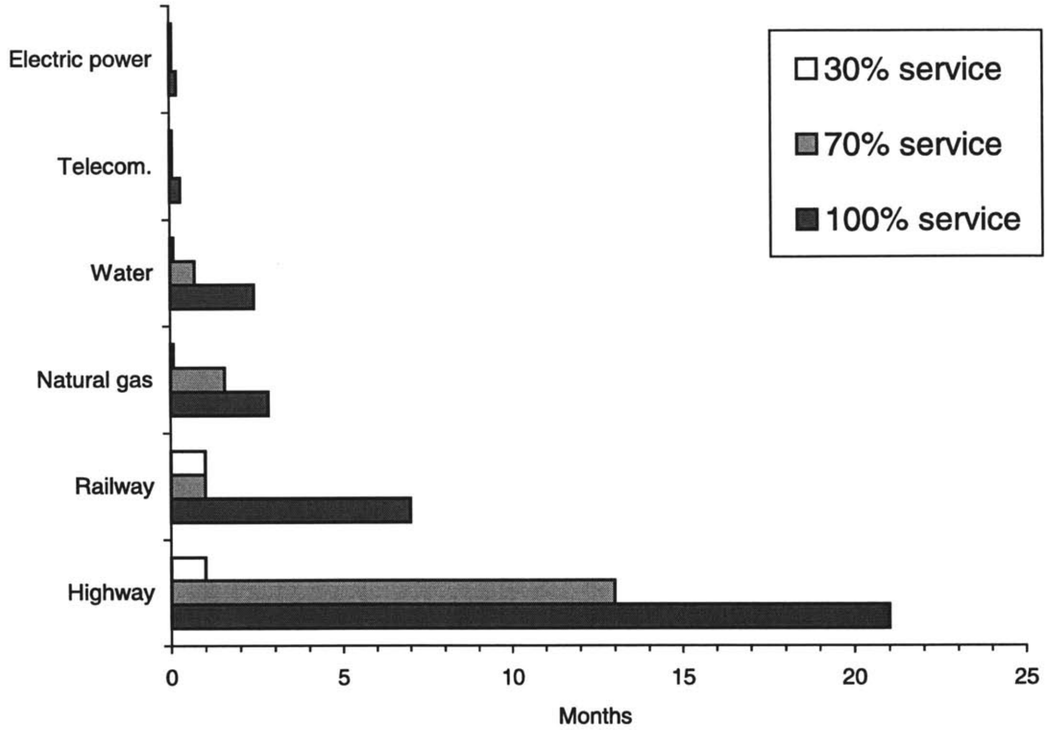

Figure 1-1: Lifeline restoration timeframe, Hyogoken-Nanbu earthquake (*Source:* Chang and Nojima (2001)

pared with other lifelines. Figure 1-1 shows the time it took to restore the various lifelines after the 1995 Hyogoken-Nanbu (Kobe) earthquake in Japan. Clearly, the transportation system was in a damaged state much after complete functionality of other lifelines was restored (Chang and Nojima, 2001). The effect of transportation network damage is thus more long-lived than the effects of damage to other lifelines.

It follows from the above discussion that transportation-related economic losses due to earthquakes are significant and warrant mitigation strategies for earthquake vulnerable regions. However, the evaluation of these losses is complex and can only be performed in an integrated and comprehensive framework, where all interactions and dependencies of the economy are considered. Further, it is important to know the component of the total loss that is attributable to the transportation system damage. Knowing this component, rational decisions about prioritizing and level of resources for mitigation can be made.

The literature lacks such a methodology in which all the important elements of loss (including transportation-related losses) are modeled in an integrated framework. Most of these studies focus on certain elements of the infrastructure or the economy in an isolated environment: for example, the effect of electric-power network failure on the economy(see, e.g., Chang (1998) and Schiff (1998)), or the direct losses of transportation network damage.

A few methodologies focus on the indirect losses due to the reduced functionality of the transportation system. Of these, some isolate the transportation system from the economic framework (see, e.g., Werner et al. (2000)). They only calculate the post-earthquake traffic flow states, and the consequent increase in travel times. Others do not consider earthquake vulnerability of other infrastructure and businesses (see, e.g., Okuyama et al. (1999)). Thus, *demand* for the transportation system is considered as an exogenous variable. This demand for the transportation infrastructure is not linked to the damage on other infrastructure and businesses. Thus, only the economic effects of a hypothetically damaged transportation network are calculated.

There is also a lack of methodologies that include *all* effects of reduced functionality of the transportation system, such as total inaccessibility conditions. Thus losses are restricted to the effects of increase in the travel times/costs. Some researchers limit the analysis to a specific region and ignore global effects of transportation network constraints (see, e.g., Shinozuka et al. (1998)). Recovery of the system elements is also an important aspect of loss estimation procedure not satisfactorily modeled in many of these studies (see, e.g., Shinozuka et al. (1998) and Okuyama et al. (1999)). All of these while representing important advances, present a limited view of the problem.

This thesis is an attempt to develop a methodology to assess the *total* economic loss in the event of an earthquake, and determine the contribution to the total loss from various components. Special focus is given to the transportation-related economic loss component. Thus, the methodology attempts to build a broader framework of economic loss estimation, though it is considerably coarser when compared with other contemporary studies. The methodology can be refined by incorporating better models as they become available, increasing resolution, and emphasizing parameters that significantly influence losses. Important parameters can be identified by computing the sensitivity of losses to various parameters in the methodology. Eventually, it can be developed into an accurate, comprehensive methodology for earthquake loss estimation.

The problem of earthquake loss estimation is complex and has a highly interdisciplinary nature due to the broad scope of elements involved. A fully comprehensive methodology is limited by factors such as the limited availability of seismic vulnerability parameters, stochasticity of component behavior, functionality and economic interrelationship parameters, computational complexity, and availability of data and models. However, with significant simplification and abstraction from the real-world, a coarse framework for studying economic impacts and sensitivity of losses to ameliorative strategies can be developed. This thesis is an attempt to develop such an integrated framework that is simple, yet broad in scope. Improvement of the methodology in terms of reduction of coarseness and improving the models for accuracy of loss estimates is however possible, and suggested.

The integrated framework of the methodology developed includes:

Engineering Models Seismic attenuation, component vulnerability, damage-functionality relationships, restoration of components after the earthquake, etc.

Economic Models Dependence of industries on infrastructure[4], industrial economic interaction, economic loss assessment, etc.

Transportation Models Transportation network performance, network flow models, etc.

Such an integrated earthquake loss methodology can be used for many purposes, including:

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[4] The term *infrastructure* in this thesis refers to the industrial, commercial, residential, lifeline and transportation structures

1. Estimating the total economic loss from a scenario earthquake and thus helping to rationally decide about the level of resources to be allocated for reducing earthquake risk.
2. Identifying the priorities for strengthening and retrofitting existing infrastructure.
3. Evaluating methods of strengthening various components for maximum enhancement of system-wide seismic performance.
4. Identifying the ideal post-earthquake measures for reducing losses and restoring functionality of the economy.

Pure scenario-based loss estimation methodologies, like the one proposed in this thesis, only give an assessment of economic loss, given a scenario earthquake. In order to rationally decide about loss-reduction measures, it is necessary to perform a risk analysis, accounting for the probability of an event in a given time period and the uncertainty on the location and intensity of future earthquakes. Developing such an extended risk analysis is beyond the scope of this thesis.

The thesis is organized as follows:

Chapter 2 discusses issues in assessing economic impacts and explains how the methodology developed in this thesis addresses those issues.

Chapter 3 reviews existing methodologies for earthquake loss analysis, with special emphasis on those that include transportation network damage. Various aspects of these methodologies are explained and a critical assessment is made of issues that are not satisfactorily addressed in these previous studies.

Chapter 4 describes the proposed methodology in detail. The various modules and components of the loss estimation methodology are presented here.

Chapter 5 includes a scenario analysis for a New Madrid earthquake[5] to illustrate the methodology. It is widely recognized that a large earthquake in this

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[5] The New Madrid Seismic zone lies within the central Mississippi Valley, extending from northeast Arkansas, through southeast Missouri, western Tennessee, western Kentucky to southern Illinois.

region could have devastating consequences on the regional Midwestern[6] economy, with repercussions at the national level (Central U.S. Earthquake Consortium, 2000). The description of the scenario includes issues in data requirements and preparation, models and parameters used.

The thesis concludes with a summary of the methodology and results of the scenario earthquake, and the need for future work.

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[6] A region of the north-central United States around the Great Lakes and the upper Mississippi Valley. It is generally considered to include Ohio, Indiana, Illinois, Michigan, Wisconsin, Minnesota, Iowa, Missouri, Kansas, and Nebraska.

Chapter 2

Issues in Earthquake Loss Estimation

This chapter addresses the main issues in earthquake loss estimation with emphasis on transportation network damage related issues. The chapter also discusses these issues in the context of the methodology proposed in this thesis.

Although earthquake loss estimation is a broad, multidisciplinary area of research involving a number of issues, some are at the core and a matter of consideration in most earthquake loss analyses. The scope of the estimation methodology is an important factor that decides the "completeness" of the analysis. In any risk analysis procedure, it is imperative to know the comparative loss contribution of each of the components in order to prioritize measures; thus there is the need to model losses comprehensively. The scale and resolution is an equally important issue because it controls the accuracy and geographical coverage of the loss estimate, as well as dictates the computational, data and knowledge requirements of the analysis. Interactions and recovery are important in an earthquake loss estimation methodology as the losses are directly controlled by these. Interactions, as discussed in Chapter 1, is directly responsible for indirect losses. As the system "recovers" after an earthquake, its functionality increases and losses diminish. Further, recovery is different for various economic sectors and infrastructure, thus the temporal dimension has to be added to the methodology to model system states over time.

Issues related to the methodological aspects of the analysis include uncertainty and non-linearity in the elements. Earthquake risk, hazard and consequent behavior of the economy all have inherent uncertainty. Uncertainty introduces significant complexity, especially as several variables in the methodology have variability. Also, the performance of most physical and economic systems is non-linear with its damage. Thus, this non-linearity needs to be addresses satisfactorily for the purpose of loss estimation.

Reducing earthquake losses requires the application of mitigation strategies. It is thus important to analyze the possible strategies within the earthquake loss estimation framework. An analysis of these strategies can be used to enable strategic decision-making regarding mitigation.

Following is a description of each of these issues, and how the proposed methodology deals with them:

2.1 Components of Earthquake Loss

The main components of earthquake loss are social losses (fatalities, injuries, homelessness, etc.) and economic losses (direct, indirect and induced losses). The methodology developed in this thesis primarily deals with the economic losses. Figure 2-1 details the broad sources of various economic losses. The direct losses are immediate, and a result of damage to man-made structures (building stock, content of buildings, lifelines, transportation infrastructure, etc.). The direct damage leads to reduced functionality of all these systems, resulting in further losses that accumulate over time until the functionality of elements is restored to pre-earthquake conditions. Induced damages originate from secondary effects of earthquake such as flooding, release of hazardous chemicals, debris, fires, etc.

Following is a description of these social and economic losses:

1. **Social Losses**

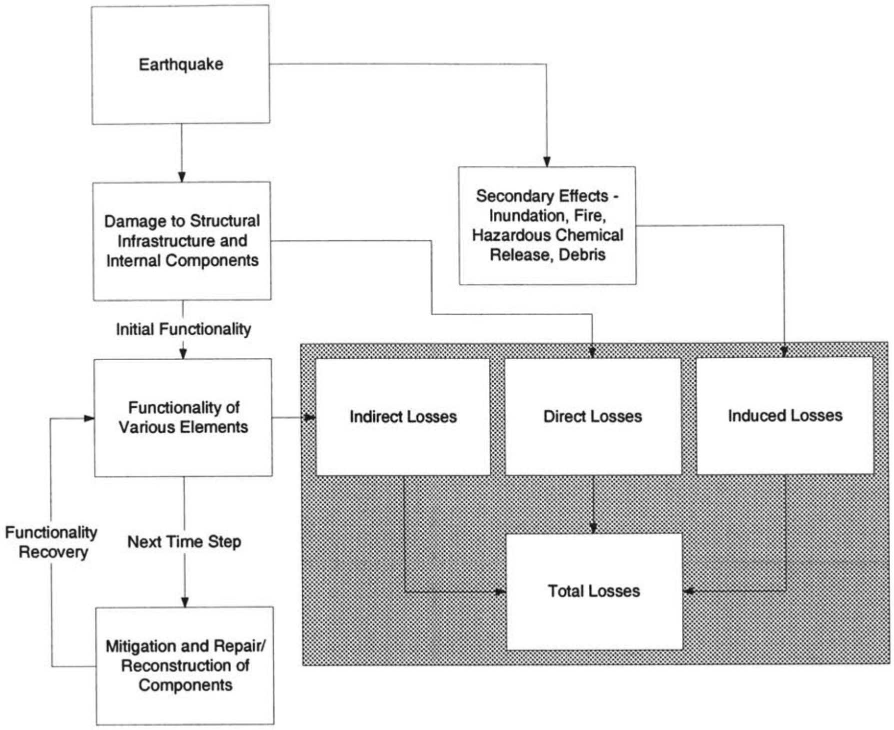

Figure 2-1: Earthquake economic losses

Earthquakes have repeatedly led to casualties and have impacted social functions within the area of direct influence. Casualties result from the damage or collapse of structures (such as buildings and bridges), or from indirect effects such as fire, floods, delayed emergency response and relief efforts, damage to essential facilities (such as hospitals), and hazardous material release. Earthquakes also cause other social losses such as homelessness, closure of, or access problems to facilities (e.g., schools and religious establishments), psychological effects (grief, trauma, etc.), and long-term social changes through adverse economic effects (such as loss of employment, etc.).

Fatalities and injuries are hard to quantify in economic terms, but have a definite contribution in formulating earthquake risk reduction strategies. Some researchers (see, e.g., Englekirk and Sabol (1991)) have focused on the question of casualties from earthquakes in an independent framework. They analyze the probability of loss of life or injuries, given levels of damage to building stock.

National Institute of Building Science's (NIBS) HAZUS (National Institute of Building Sciences, 2000a) loss analysis framework includes casualties and homelessness. The mechanism used to calculate casualties and homelessness is based on, and limited to the damage suffered by structures. There is a lack of models that can predict these casualties due to indirect effects (fire, floods, etc.). Due to the intangible nature of other social losses (such as psychological effects and changes in social patterns), it is virtually impossible to build quantitative models that evaluate these effects.

2. **Economic Losses** Economic losses are categorized as direct, indirect and induced.

    (a) *Direct economic loss*

    Direct losses include the costs of repairing or rebuilding damaged physical infrastructure and contents. All infrastructure is vulnerable to earthquakes to a certain degree. These vulnerabilities are used to estimate the damage states of each category of building stock and the associated replacement and repairing costs. Applied Technology Council's ATC-13 (Applied Technology Council, 1985) is the most widely recognized document for calculating direct loss and damaged states of various structural categories for different ground shaking intensities. The *damage factors* described in ATC-13 and other documents give the factor of dollar loss to replacement value. Thus, knowing the replacement value of the structure, direct loss can be calculated.

    Direct damage is however highly probabilistic (Applied Technology Council, 1985) because the seismic performance of individual components cannot be accurately predicted (see Section 2.5). In addition, many structures like individual bridges have not been evaluated for seismic performance and only aggregated performance measures based on certain characteristics of the structure can be used for modeling their vulnerability. For example, Hwang et al. (1998) have carried out an analysis of bridges in the Shelby

County, Tennessee, and aggregate bridges in 5 categories for the purposes of developing fragility curves[1]. Such techniques of aggregation are widely used for the formulation of intensity-damage relationships for structures.

(b) *Indirect economic loss*

Businesses are linked to each other, and depend on lifelines and its own infrastructure to function. Earthquakes may produce dislocations in this economic framework by damaging the infrastructure and lifelines, resulting in indirect losses.

Earthquakes damage economic sectors and lifelines in the geographical area sustaining direct impacts. These damages in turn are responsible for loss of business. Damages can affect businesses by reducing their productivity or making it impossible to produce goods (e.g., damage to critical machinery, or structural collapse to the building housing the industry can interrupt production). Earthquakes can also reduce functionality of businesses due to bottlenecks in damaged lifelines (e.g., damaged electric-power distribution network and consequent power outages can lead to shutdown of high-technology manufacturing units.).

The other form of indirect losses comes through a complex system of linkages in the economy (see Section 2.3). Each industry requires commodities and services from other sectors of the economy and also depends on consumers (both companies and individual consumers) to buy their produce. Dislocations in economic framework through directly or indirectly affected economic sectors thus causes further losses throughout the economy. It should be noted that these losses are not confined to immediate customers or suppliers of damaged enterprises. All of the successive rounds of customers of customers and suppliers of suppliers are impacted. In this way, even limited earthquake physical damage causes a chain reaction, or ripple effect, that is transmitted throughout the regional economy.

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[1] A fragility curve displays the probability that a structure is damaged beyond a specified damage state at various levels of ground shaking

Indirect losses accumulate over time until the functionality of elements is completely restored, or to an extent that its use is not constrained by the damage. Even though direct economic loss might appear substantial, analysis and past experience has shown that indirect loss is usually on the same order, or larger than direct loss (Shinozuka et al., 1998). Indirect losses are much harder to estimate than direct losses because the interactions greatly increases the scope of the analysis. These interactions also add geographical and temporal dimensions to the analysis as the businesses are spatially distributed and the whole system state changes over time after the earthquake by differential restoration.

(c) *Induced economic loss*

These include losses due to secondary effects of earthquakes such as flooding, landsliding, debris, fires and the release of hazardous chemicals.

Fires are often caused by earthquakes and may account for a sizeable portion of the total economic loss. The hazard of fire is highly stochastic and depends on local variables such as presence of flammable material, emergency response infrastructure, weather conditions, etc. Though some studies have attempted to incorporate this hazard, the models developed remain empirical and uncertain. FEMA's HAZUS (National Institute of Building Sciences, 2000b) uses data on fires from previous earthquakes to estimate the number of ignitions, area affected, and population and building stock exposed to fire hazard.

Damage due to flooding may be due to tsunamis[2], seiches[3] or failure of dams or levees (National Institute of Building Sciences, 2000b). Researchers have studied the earthquake vulnerability of structures such as dams and levees in detail. However, little work has been done to estimate induced economic losses due to flooding as a consequence of earthquakes, mainly due to the difficulty in modeling such uncertain effects.

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[2] Seismic sea waves, generally affecting coastal regions

[3] Sloshing in lakes and bays

> Hazardous chemical release is also an induced loss that can pose significant threat to life, property and the environment. Depending on the type and geographical scope of hazardous material (hazmat) release, the damage can either be limited to a small region, or affect regions far beyond the extent of the earthquake. No usable models that can predict the likelihood of occurrence of hazardous materials releases during earthquakes have been developed (National Institute of Building Sciences, 2000a). However, HAZUS uses a simple model that can locate susceptible areas through an inventory of facilities containing hazardous material. No attempt to quantify the economic impact of such releases has been done.

The methodology proposed in this thesis only considers economic losses. Though social losses have a very important impact, they are hard to model and quantify. Of the economic losses, direct damage loss to building stock (residential, commercial and industrial), lifelines and highway components (bridges and pavements) are included. Indirect losses of earthquake modeled include effects of damage to infrastructure and lifelines, and dislocations of the economy through input-output linkages. The methodology developed lacks a module for calculating induced losses due to the their extremely complex, unpredictable nature, and the lack of existing models. Even though modeling these losses is beyond the scope of this research work, the models can be adapted to include these losses with improvement of the knowledge base in understanding these effects. The scope of the methodology allows for integration of these effects into the loss estimate.

2.1.1 Transportation-related Losses

While the methodology developed in this thesis includes a broad spectrum of direct and indirect economic losses, it emphasizes the loss component due to damage to the transportation network by modeling the transportation system in more detail than other systems. The losses exclusively due to the transportation network damage (or any other component) can be dissagregated from the total loss by assuming it to be invulnerable to earthquakes in the analysis and assessing the difference in total loss, with and without this assumption. This *difference* can be used as an approximate indicator of the contribution of that component towards the total earthquake loss.

The losses due to transportation network damage can be further disaggregated for the purpose of understanding and analysis. Earthquakes have the direct effect of damaging the transportation infrastructure, leading to direct economic losses. Further, this damaged infrastructure can lead to bottlenecks in the transportation networks leading to delays and access problems, and associated economic losses.

Following is a brief summary of transportation-related economic losses:

1. **Loss due to direct damage to transportation infrastructure**

   These losses include the replacement or repairing cost for transportation network components such as highway pavements, bridges and embankments. Several studies have been undertaken on the seismic performance of transportation network elements. For example, Hwang et al. (1998) have developed fragility curves for a system of 5 bridge classes. Mander and Basoz (1999) have developed a theoretical basis for establishing fragility curves for bridges in the U.S. Other fragility curves for classes of bridges or for individual bridges have also been developed based on empirical as well as experimental data (see, E.g., Jernigan and Hwang (1997)). These fragility curves can directly be used to assess the damages and losses if the intensity of ground shaking at the bridge site is known.

2. **Indirect losses**

   Direct damage to transportation network components reduces the functionality of the transportation system, and can cause congestion or inaccessibility conditions. The business interruption losses are affected by these increased travel times and bottlenecks for general traffic. The traffic composition broadly includes freight, commuters, shoppers (home-to-shop, or shop-to-home) and leisure travelers. While the losses due to delays are relatively simple to model by attaching a value of time to each of the constituents, indirect losses due to

> constraints that totally inhibit traffic flows are complicated by the issue of linkages in economy (see Section 2.3). These total inaccessability conditions create shortages through delivery problems and thus affect the productivity of industries, both within and outside the direct influence of the earthquake. Similarly, transportation-related access problems to employees results in lost productivity. These effects were fairly noticeable during the aftermath of the Northridge earthquake (Gordon et al., 1998), primarily because the earthquake had an urban scope of influence. Further, access problems to consumers causes direct loss of revenue, or costs in terms of relocating businesses.
>
> Another form of indirect losses includes increase in fuel costs due to the increase in distance traveled by both freight and passengers. These losses are relatively small and easily modeled as a direct function of the increase in travel distance and time. Only a few researchers have undertaken to include these losses because of their small contribution to the total loss (Werner et al., 2000).

The methodology developed here concentrates on the significant contributors to transportation-related economic loss: (1) direct damage loss, and (2) indirect loss due to increase in freight traffic travel time or bottlenecks that totally inhibit access, thereby creating input shortages or delivery problems. The other forms of indirect losses, including delays and access problems to commuters and other passenger flows are more pronounced on an urban scale of operation. Urban flows, unlike interregional flows, are predominantly passenger based traffic flows. These require a thorough, detailed microscopic analysis for each region affected, and cannot be attempted over a large geographical area due to computational and data limitations. For example, Shinozuka et al. (1998) consider these flows, but only in the L.A. metropolitan area.

In the methodology proposed in this thesis, certain microscopic effects can be captured through parameterizations of transportation damage effects on an urban scale. This is achieved by incorporating performance parameters on the node level, thus modeling aggregate damage and functionality of systems like the transportation network. These parameters on the nodes can be used to assess the loss-of-functionality effects on other classes of the economy (see Section 2.2 for details) without modeling the system in detail. A detailed microscopic analysis on the node level is beyond the scope of this work.

2.2 Scales and Resolution

Earthquake loss analysis can work at several scales and resolutions. The effects of an earthquake can be global (see Section 2.3). Thus, ideally, a comprehensive and accurate analysis should have a scale that includes the economy of the entire world for the purpose of loss analysis. The analysis should also be detailed, so that all local conditions and effects are captured completely and accurately in the model (for example, soil conditions, spatial distribution of building stock, vulnerability of individual elements, etc.).

However, there are several constraints that limit the scale and detail that can be modeled in an earthquake loss analysis. Such constraints result from limitations in computational resources, availability/scope of data and knowledge base. A model that operates at a large geographical scale and includes detail can require immense computational resources, especially if the algorithms involved in the analysis require optimization. As an example, models that take into account the transportation network constraints for loss analysis should ideally include the complete transportation network of local, secondary and primary roads. However, the immense size of the U.S. highway network limits any detailed optimization on this transportation network for the analysis of constraints (from damage to the network) in the network. Researchers have thus abstracted from the real network in an attempt to make the problem computationally feasible. For example, Okuyama et al. (1999) only consider the interstate highway network in their analysis. The highways crossing the boundaries of their system of regions are consolidated to develop an abstract network of links with aggregated capacities and costs. Werner et al. (2000) have used a detailed network for their analysis, but had to limit the scope of their study to a single urban area (Shelby County) due to data requirements and to make it computationally feasible.

In several models, the data and information required for a detailed analysis is either restricted or unavailable. For example, bridges in the Midwest region of U.S. were not designed to resist earthquake loads (Hwang et al., 1998), and detailed data regarding their earthquake vulnerability is not available. It is difficult and prohibitively expensive to collect data for individual structures. Researchers thus use abstraction or classification of data into rough categories to approximate the unavailable data. For example, Mander and Basoz (1999) have developed analytical fragility curves for the highway bridges in U.S., classified on the basis of commonality in structural features such as span and type of construction. These models however loose resolution in terms of modeling detailed behaviour of each element.

Availability of knowledge is a major factor limiting the accuracy with which earthquake effects can be predicted on a detailed level. For example, the literature lacks usable, completely developed models of local economy for the entire U.S., restoration functions for several individual structures, fast network performance models, etc. These limitations thus limit the scale and detail that can be modeled in an integrated methodology.

The methodology proposed in this thesis operates at a broadly macroscopic scale. The geographical span of the analysis covers the entire U.S. through an abstract representation of nodes (aggregated regions) and links (highways). A balance between scale and detail is attempted for computational feasibility and to deal with data limitations, without losing much accuracy. For example, the transportation network in the area of direct impact has more detail than the rest of U.S. and includes all primary roads[4]. As the damage to the network is limited to the region around the epicenter, the effect of this damage through constraints is modeled more accurately.

Also, further methodological work will attempt to increase the accuracy of the loss estimate on the macroscopic scale by using parameters developed from microscopic models. Microscopic models have a higher resolution than the macroscopic models. These microscopic models can be used to develop aggregated parameters

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[4] Primary roads include Interstates, U.S. and State Highways

that can be used in macroscopic models. For example, by microscopically modeling the transportation network in an urban area (each bridge, pavement, etc. modeled, and network analysis performed), the detailed effect of transportation network damage to economic sectors can be evaluated. Aggregate parameters describing the effect of network damage on the economic sectors in urban centers can then be developed. These aggregated parameters can thus describe the effect of a certain level of damage to the transportation network (without exactly detailing which bridges, pavements, etc. are damaged), on a particular economic sector in the urban center. Finally, these parameters can be utilized in the macroscopic model of a broader geographical scope, avoiding the need to model each "node" in the region in detail. The behavior of economic sectors due to nodal transportation network damage can be evaluated using the parameters developed from the microscopic models. Even though these parameters will not account for the complete system configuration of each node, and produce certain inaccuracies in the loss analysis, they can provide rough estimates of these local effects.

2.3 Interactions and Recovery

Interactions in the economic framework add significant complexity to the problem of economic loss modeling. All businesses either sell their products (forward-linked), or rely on other businesses to provide inputs (backward-linked) (National Institute of Building Sciences, 2000c). These businesses are vulnerable to economic losses if either the supply or demand is disrupted. Further, the losses due to damage and constraints are not limited to the direct customer or supplier, but are also carried over to all of the preceding/following businesses in the supply chain. The ripple effect may be felt at larger economic scales and is not limited to the regional economy. Thus, even a region far from an earthquake may be affected by indirect economic losses.

The Taiwan earthquake of 1999[5] is a notable example of the global effects of

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[5] Taiwan suffered a 7.6 scale earthquake at 1.45 am on 21 September 1999, the worst in a century for the island, with the epicenter at Chichi village in the island's central Nantou County.

earthquakes. Taiwan is a major exporter of computer components, especially memory chips, to the US and the rest of the world. The shortfall in production caused by earthquake damage in Taiwan led to a drastic increase in the prices of computers and components across the globe (Papadakis, 2000). Thus, for holistic modeling of economic losses, these indirect effects have to be incorporated. These linkages are however very complex and are defined by several variables including inventory levels, employment levels, alternate sources and outlets, insurance and recovery. For instance, inventory levels in industries can buffer the impact of shortages in the short run.

Input-Output models[6] provide a framework for the analysis of inter-industry interactions. These models trace the requirements and productions of industrial sectors and consumptions by governments, households, investments and exports. In these models, inputs used in producing a product are related to the industry output by a fixed coefficient production function. These coefficient functions thus represent the dollar amount of each commodity required to produce a single dollar worth of products. Thus, a framework is developed in which inputs and outputs are related, enabling the study of ripple effects in the economy due to shortages of any of the inputs. These models are extremely data-intensive and range from simple local models to highly complex regional or national models.

For the purpose of loss analysis in this thesis, significant aggregation and simplification was required to reasonably model the interactions in accordance with the available knowledge, data and computational resources. For instance, the same model for input-output interaction was applied to the whole U.S., avoiding involved complex and varying models on smaller scales. This loses detail and accuracy, but simplifies the process to an extent that it can be modeled in the methods developed. Also, the industries were aggregated into 13 categories for the purpose of this input-output analysis to simplify the model. Further work towards improving the methodology would attempt to assess the inaccuracies in the loss estimate created by these sim-

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[6] First formulated by Nobel laureate Wassily Leontief and later refined by several economists (National Institute of Building Sciences, 2000c)

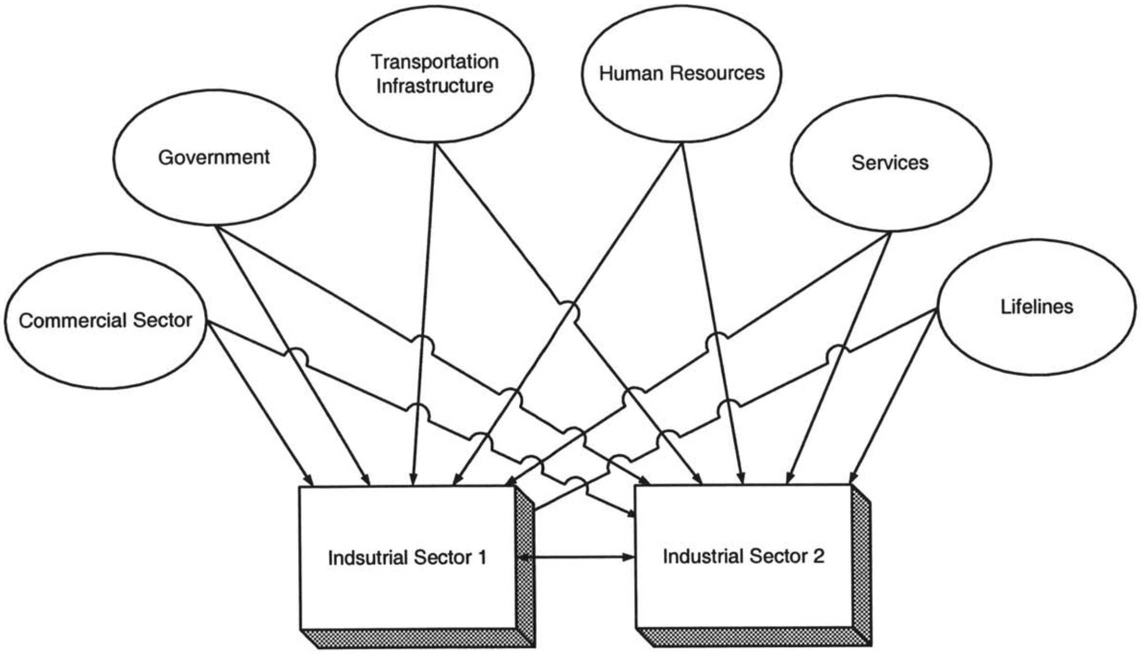

Figure 2-2: Interactions

plifications. An appropriate system of simplifications can thus be adopted for an accurate analysis.

Besides the interindustry interactions, all businesses rely on lifelines (such as transportation infrastructure, electric-power distribution network, water networks, etc.) and human resources. Business losses are thus related to the performance of lifelines, and the level of employment in the post-earthquake state. The level of dependence on lifelines and other resources varies by industrial sectors, and in some cases can be very high. For example, the electrical network is an essential input to industries such as high-technology manufacturing, and damage to the electricity distribution infrastructure can cause total shutdown of the industry. Similarly, most industries rely on the input of commodities from other industries, and thus rely heavily on the transportation network. Capacity constrains that limit or delay the flow of these commodities can have severe impacts on the productivity of such industries. Figure 2-2 shows a simple 2 industry model that interacts within itself (through input-output models) and depends on several other lifelines and resources.

Interactions are closely related to restoration of lifelines and infrastructure. Earthquakes affect the general population and economy for an extended period of time.

However, every component of the system recovers at a different rate and economic loss analysis of dislocations in the network of economic sectors should consider functionalities over time. For example, the electrical system often recovers in a short period of time, while the transportation network takes substantially longer to recover (Chang and Nojima, 2001). Thus, the total loss should reflect losses accumulated over the evolving system states in the post-earthquake scenario. Restoration is also directly related to the functionality of various elements of the system. With a damaged transportation network, it will be difficult to transport structural materials to rebuild building stock (also see Section 2.6 for details on issues in rebuilding priorities).

The methods developed in this thesis explicitly models restoration. The losses are accumulated over discretized time steps in the post-earthquake scenario. The parameters of this restoration model can be changed to reflect strategic decisions about reconstruction (e.g., speeding up recovery by increasing the level of resources allocated).

2.4 Non-linearity in System Performance

The performance of lifelines like electrical systems, transportation networks, and water, oil and gas distribution networks are non-linear with respect to the damage to individual components. For example, the failure of a strategic bridge in a transportation network can greatly constrain the system; on the other hand the damage can be inconsequential if there is redundancy or the bridge is lightly used. The network system can either buffer the effect of an individual element with reduced functionality, or the effect can propagate along the network, significantly impacting the performance of the whole system. Similarly, there are non-linearities in the economic framework. For example, production and consumption levels of industries depend on many factors and are non-linear with damage to a certain element. Such systems are hard to model accurately.

The methodology developed attempts to model the non-linearity of system performance in many elements, such as the interregional transportation system. By preserving the transportation network topology, and performing an optimization to predict the flows on this network, the *network* effect of damage to a certain element is considered. It is however beyond the scope of this thesis to model non-linearities in *all* systems such as lifelines (oil & gas, power-electric, telecommunications network, etc.).

2.5 Uncertainties in Earthquake Risk

It should be considered that the problem of loss assessment following an earthquake is replete with uncertainty and variability. Even under a prescribed earthquake scenario, there is significant variability in the ground motion produced by the earthquake and therefore in the consequent damages and losses. There is also uncertainty on the behavior of physical infrastructures under a given ground motion, the loss of functionality parameters and the effects on the economy at various geographical scales. The uncertainty in the proposed methodology is especially high as several variables and parameters have been internalized in the process of evolving a comprehensive methodology. Some of the highly stochastic variables in a complete earthquake loss estimation methodology include:

- The stochastic nature of earthquakes: Spatial location of earthquake epicenter, ground motion, intensity, time of event, etc.
- Geological behavior: landsliding, liquefaction, local site-conditions, etc.
- Earthquake hazard: Vulnerability of infrastructural classes, damage-functionality relations, fire, flooding, etc.
- Social and economic behavior: human response to earthquake (political, general public, response management agencies, etc.), restoration budgets, modal choice, route choice, inventory levels, economic input-output restructuring, etc.

An attempt to address the issue of uncertainty has been made in the analysis. However, explicitly modeling uncertainty in a comprehensive system increases the size of the problem by enormous proportions and makes the problem unsolvable. Thus, for simplicity and feasibility, the model uses deterministic parameters for the analysis. There is scope for further work in this respect to explicitly include reasonable uncertainty in the models, or improve the accuracy of the analysis through Monte Carlo simulations of earthquake scenarios.

2.6 Strategies to Reduce Earthquake Loss

The ultimate purpose of the methodology is to assess the total losses from an earthquake and its constituents, and thus provide a tool for reducing economic loss in the event of an earthquake. In that context, it is important to understand the strategies available to reduce the impact. A *risk assessment*[7] of each component complemented by a *cost-benefit* analysis can be used to decide the optimal risk reduction strategy.

Following are some possible risk reduction strategies:

1. **Strengthening the infrastructure**

   Strengthening the infrastructure yields benefit in terms of reducing both direct and indirect losses. By hardening the vulnerable physical components of the region, direct damage will be ameliorated in the event of an earthquake. This also reduces the possibility of further indirect economic loss through extended reduced functionality and restrained capacity (see Section 2.3). In the transportation context, strengthening a bridge not only yields benefit by reducing the damage to the structure from seismic activity, but also reduces the possibility of delays and interruptions. By avoiding these delays and interruptions, economic losses to businesses that directly or indirectly depended on the transportation system are reduced.

   Much research focus has been given to upgrading building structures to enhance the seismic performance of structures. A typical example of strengthening high-

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[7] In a generalized sense, risk assessment is the qualitative or quantitative estimation of the likelihood of adverse effects that may result from exposure to specified hazards or from the absence of beneficial influences.

way bridges is retrofitting using the column wrapping[8] method (Foster, 1997). The city of Seattle experienced an earthquake of magnitude 6.8 on Feb 28, 2001. The city government had recently implemented a retrofitting program for 15 of the city-owned bridges (Mitchell et al., 1999) using varied bridge foundation strengthening schemes. It is believed that the retrofit program avoided damage or collapse of these bridges, and further economic losses.

2. **Constructing redundant infrastructure**

   Losses can also be reduced by increasing the redundancy in the system. Issues of redundancy are important in network systems, where the losses due to individual element functionality are non-linear, and instead are a function of how the complete system behaves. Hence, a bridge might be highly susceptible to a low-magnitude earthquake, yet not yield significant economic impact in the presence of a redundant, less vulnerable bridge in the vicinity that provides a short detour. Redundancy can be a vital safeguard against economic losses and can substitute for strengthening the infrastructure. Inherent redundancy in the system has helped in curbing economic loss in historic earthquakes; the transportation system of Los Angeles is a good example where economic losses due to the Northridge earthquake would have been much higher in the absence of sufficient redundancy (Kamel and Parks, 1996).

3. **Changing the spatial economic structure**

   Losses have a strong correlation with the spatial economic structure. The interdependence of the industrial classes causes indirect economic losses across the system, even if an individual component is not directly effected. The Midwestern region of the United States is at risk of a major earthquake (Atkinson et al., 2000), and the region is strategically important because of its geographical position in the central U.S., and a supplier of commodities to other regions (Bureau of Transportation Statistics, US Department of Transportation, 1997). A

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[8] short note on column wrapping

change in the spatial economy and land-use planning with less dependence on this region or focusing newer development in less vulnerable regions can reduce loss.

4. **Improving seismic design criteria and specifications for new construction**

   The advances in the field of earthquake engineering can be used to modify the existing specifications for better seismic performance of structures. Existing design criteria have often been found insufficient in resisting seismic loads and numerous studies have concentrated on the improvement of these specifications (see, e.g., (Rojahn et al., 1997)). The Midwest region of the U.S. is highly susceptible to earthquakes of great magnitudes. However, these earthquakes are infrequent and the basic design criteria developed for this regions lacks sufficient earthquake resistance, discounting the importance of these infrequent earthquakes. A scenario loss analysis which can predict the total earthquake loss in any region may thus yield benefit in terms of exposing the vulnerabilities and warrant a redesign of the building specifications and requirements.

5. **Rebuilding priorities**

   Economic losses can be reduced in the post-earthquake scenario through strategic decisions on rebuilding of the damaged infrastructure (Lee and Dargush, 1997). The recovery activities are a function of the social, economic, physical, technological and political systems involved and operate on different time scales (Cole, 1998). Certain activities such as providing medical and shelter needs and attending to other life-threatening issues naturally take precedence over other restoration activities. However, in the context of long-term goals of reducing economic loss, restoration should be viewed in terms of interactions, criticality, and economic significance of each element to be restored.

   In the process of restoration after an earthquake, several resources are allocated to mitigate and repair or rebuild the damaged infrastructure. The functionality of the elements is thus gradually restored over a period of time. This process involves several strategic and policy decisions, like:

- Which individual component should be restored first?
- What level of resources should be used to restore a facility, given the fact that higher level of resources can speed-up recover?
- Which industrial class should be given any incentive or assistance, if at all, to restore its production capacity?
- Which lifeline should get more restoration focus?

These questions have social, economic and political aspects, and need to be addressed through a decision model supported by analysis of the effectiveness of various strategies in post-earthquake scenario. For example, the transportation network may have a damaged link which required a lengthy detour. It may be intensively used because of its strategic location. Thus, relatively more resources should be allocated towards the restoration of this critical bridge. Also, different repair strategies are available, each having its associated cost, that provide different repair times (Yashinsky, 1999). Other decisions such as deciding which lifeline is to be restored first are however complex, and dependencies in the economic framework, restoration and functionality of other components, and the repercussions of reduced capacity need to be considered (see Section 2.3).

Besides the engineering factors discussed above, there are economic factors that decide reconstruction strategies (Lee and Dargush, 1997). Example of economic factors include the availability of funds for reconstruction, repair versus rebuilding strategies, pre-earthquake strengthening versus post-earthquake repair, and source of funding for the reconstruction effort[9] (Lee and Dargush, 1997). There are also limits on construction capacity in the form of limited availability of construction equipment, building materials, man-power, etc. Thus, it might

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[9] Sources of funds can be varied, e.g., government funding, privatization, insurance, and private funding

not be possible to reconstruct all of the damaged facilities at the same time, requiring a prioritization procedure. Also, the cost of reconstruction is indirectly proportional to the time required to reconstruct it. By using more resources, a damaged facility may be reconstructed faster. For example, a facility may be reconstructed in 10 days using a certain levels of resources; doubling the level of resources may be able to reconstruct the facility in 7 days. The speed of reconstruction can however be saturated after a certain level of resources have been used, and additional resources may not be able to speed up the reconstruction efforts further. Such limitation arise due to logistics and engineering issues, such as people getting into each others way, etc.

Political and societal factors in restoration include issues regarding communication between the government and public, "fairness", social perspectives of development, etc. Thus, engineering factors may dictate a particular reconstruction strategy for the overall benefit of the regional economy, but the strategy may leave a particular community disadvantaged (Cole, 1998). It may therefore be imperative to modify the strategy to serve the needs of *all* communities. Thus, while there may be economic advantages in pursuing a particular repair strategy, the needs of the general public may dictate an all-round reconstruction effort. The societal and political factors also imply that the strategy has to be flexible to accommodate evolving policy decision and needs of the public. Preparedness for catastrophic events is generally low in normal times, and even if preparedness is high, it is not reasonably possible to plan for all possible post-earthquake scenario configurations (time-of-day of earthquake, intensity, location, etc.). Thus, the decisions evolve over time in the post-earthquake scenario, changing to accommodate new information (such as damage data, economic data, societal needs and perceptions, etc.) as and when they are received and analyzed.

6. Operating practices during recovery

Vital issues that come into play in operating practices include policy decisions, social and economic considerations, resource allocation, coordination between agencies, information flow and response planning (Lee and Dargush, 1997). Emergency response and relief efforts take precedence over other operating practices. However, in a longer time frame, a framework for operations in the damaged system state has to be planned for minimizing losses. Simple operating practices include traffic flow management on a damaged transportation network, introduction of temporary public transportation systems, changes in work hours to reduce transportation demand, etc. These practices require co-ordination and planning on the part of the government. Also, these operating practices have to be integrated with the recovery of structures. With immense damages, recovery efforts, limited data availability, and several decision variables (such as social and economic considerations), post-earthquake operation planning is a daunting task.

7. **Preparedness**

   Preparedness for disaster management and the infrastructure for the recovery of basic facilities can greatly reduce economic loss, casualties and injuries, especially in the initial phase. Training of disaster mitigation experts to deal with such calamities, public instruction about earthquake safety and alert warnings are other ways of increasing preparedness. Also, policy decisions, co-ordination efforts and resource allocation can all be streamlined if the agencies are prepared for such an eventuality. For example, in a large New Madrid earthquake, several states would be affected. Mitigating losses on a national scale would thus be difficult in the absence of pre-earthquake codes of conduct and coordination framework between these administrations. Similar frameworks within the agencies of the states (local and state governments, emergency response management systems, planning agencies, etc.) is also crucial for effective earthquake loss mitigation.

The integrated methodology developed in this thesis provides an ideal framework for the analysis of various strategies enumerated above. The strategies can be incorporated in the model by changing different parameters (such as recovery of components) and changing vulnerability of the structural inventory[10]. Also, the probability of earthquakes, associated hazard, cost-benefit of pre-earthquake strategies, and optimal post-earthquake recovery process and operating procedures can all be evaluated together in an integrated framework to evaluate the comparative benefits of pre- and post- earthquake strategies. For example, strengthening a bridge may offer benefits in terms of reducing losses in the event of an earthquake. However, the same level of funds may be used in post-earthquake scenario to reconstruct the bridge in a reasonably short amount of time. Thus, it might in some cases be beneficial to leave the structure un-retrofitted. There are however several other parameters in this analysis framework, including casualties, probability of an earthquake, parameters of the earthquake, etc. For instance, if the region is susceptible to a high intensity earthquake, pre-earthquake retrofit might not offer any benefit at all. Post-earthquake availability of funds will however help in rebuilding/reconstructing the facility quickly, and in avoiding further loss.

The methodology can also use sensitivity analysis as a powerful tool to analyze the economic marginal benefit of the strategies. By knowing the sensitivities of loss to various parameters in the system, priority can be assigned to the parameter with the highest sensitivity or loss reduction potential.

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[10] For example, retrofitting can be modeled by increasing the seismic vulnerability of bridges, or different rebuilding strategies (funding levels, distribution of resources for rebuilding,etc.) analyzed by changing recovery curves of different inventory elements

Chapter 3

Literature Review: Earthquake Loss Estimation Methodologies

This chapter briefly reviews earthquake loss estimation procedures and points at the need for additional developments. A discussion of several issues not addressed satisfactorily in these models is presented, and the capabilities of the proposed methodology in addressing them.

This chapter reviews earthquake loss estimation methodologies that explicitly model the losses due to transportation network damage, as well as some important loss analysis methodologies that lack this capability. The methodologies that include transportation-related losses are: Economic Impacts of an Earthquake in the New Madrid Seismic Zone: A Multiregional Analysis (Okuyama et al., 1999), Seismic Risk Analysis of Highway Systems (Werner et al., 2000), and An Integrated Model of Highway Networks and the Spatial Metropolitan Economy (Shinozuka et al., 1998). In these studies,

1. Okuyama et al. (1999) focus on economic commodity flow between regions and how limited capacity causes economic losses, without modeling the earthquake vulnerability of the infrastructure.

2. Shinozuka et al. (1998), include a broad array of economic earthquake losses including the transportation network damage. However, the models developed in the methodology are specific to the economy of the Los Angeles metropolitan region and

ignore the effect of restoration.

3. Werner et al. (2000) model increases in travel times and the associated economic losses on an urban transportation network damaged by an earthquake though advanced traffic flow models.

Other broad-scoped studies do not include the indirect effects of a damaged transportation network; HAZUS (National Institute of Building Sciences, 2000a) is an extensive earthquake loss modeling system, but does not include the transportation system-related economic losses (e.g., increase in travel times, or indirect economic losses due to accessibility problems). ATC-13 (Applied Technology Council, 1985), developed by Applied Technology Council, gives expert opinion on damageability, functionality losses and infrastructure inventory classifications for seismic vulnerability. The document however does not deal with indirect economic losses in the damaged system. Other researchers have studied the vulnerability and economic effects of disruption of individual lifelines. For example, Chang (1998) and Schiff (1998) study the vulnerability of electricity distribution network, and Owens (1999) has developed a framework for evaluating the vulnerability of oil pipeline networks. A good deal of work has been done on the engineering aspects that deal with vulnerability of individual structures and infrastructural classes, infrastructure retrofitting methods and geological aspects of earthquake risk. Several journals such as *Earthquake Spectra* and *Earthquake Engineering & Structural Dynamics* have an earthquake engineering focus. Though the emphasis of this thesis is on transportation-related economic losses, it is useful to discuss a few studies that do not explicitly include transportation network losses. The input of these is helpful in developing an integrated framework where other losses and engineering aspects of earthquake loss estimation are also modeled.

The rest of this chapter reviews the main state-of-the-art methodologies, with and without transportation network damage.

3.1 Earthquake Loss Estimation Models Including Transportation Network Damage

3.1.1 Economic Impacts of an Earthquake in the New Madrid Seismic Zone: A Multiregional Analysis (Okuyama et al., 1999, UIUC)

The paper aims at estimating the indirect losses caused by an earthquake affecting the transportation network. The model incorporates interregional commodity flows and inter-industry relationships. For the analysis, the entire US territory is divided into 36 Earthquake Analysis Zones (EQAZ) and the transportation network is represented by the US Interstate Highway system. Industries are classified into 13 sectors for modeling their interactions in the input-output economic framework (see Section 2.3).

The economic loss model in the study integrates the Standard Interregional Flow Model[1] with a Transportation Flow Model. The economic impact of an earthquake is estimated by solving the integrated model before and after the earthquake as a minimum cost flow problem. The constraints in the optimization problem include capacity constraints (on the link capacities) and the node balance constraints (difference of commodity entering and leaving a node is equal to the import or export from the node). The problem is thus solved as an optimization problem, with regions (nodes) representing sources and sinks of commodities in the network. The model also includes *crosshauling*[2], thus incorporating realism in terms of representing flows. The economic losses due to disruption of the transportation network are thus found as the transportation costs associated with the increase in travel distances and time due to the reduced capacity or elimination of transportation links. Transportation con-

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[1] The model of flow of commodities across regions through the input-output economic framework

[2] Crosshauling implies that a particular commodity can flow in both directions on any particular link or between an OD pair. In an analytical optimization problem formulation, crosshauling is not possible as the transportation cost can be decreased by having flow in only one direct (equal to the difference of flows in either directions in the crosshauling case). In reality however, crosshauling exists due to randomness in the system, aggregation of commodities (components of which might be flowing in opposite directions), etc.

straints are also assumed to affect the regional economy by changes in final demand (consumption by general population); thus, if the network is greatly constrained, the final demand in impoverished regions can change, inducing indirect losses in the system. The input-output model together with the transportation flow model is used to estimate these changes. Following the earthquake, different hypothetical scenarios are analyzed where different links (highways) are disconnected.

The model can be used as a tool to identify critical links in pre-earthquake analysis and to determine optimal flows and losses due to increased travel time for post-earthquake scenario conditions.

The methodology however does not incorporate engineering risk and vulnerability of infrastructure, and assumes that the demand for the transportation system is not sensitive to the functionality of the industries and other economic sectors. The demand is thus taken as exogenous, though it can be varied by using other seismic performance and infrastructure inventory models. The *links* in the model are considered to be the aggregated capacity of interstate highways crossing the common boundary of regions (aggregated as *nodes*).

The methodology does not completely model the transportation network configuration. Considering a highly abstract network of nodes (region centroids) and links (aggregated highway sections crossing the mutual boundary of regions) aggregates the system configuration of the transportation network such that the real network connectivity is lost. Ignoring minor roads also loses the effect of possible redundancy in the system and will thus result in overestimated losses. In contrast, the methodology proposed in this thesis tries to model the transportation network in its representative form by modeling Interstate highways in the transportation network. By reducing the scale in the affected region, all primary roads (Interstates, U.S. Highways, and State Highways) are modeled.

The methodology of Okuyama et al. (1999) is however clearly more advanced in modeling the economic input-output system and transportation network flows than the methodology developed in this thesis. As opposed to the methodology developed in this thesis, it also incorporates mode choice analysis and models rail freight traffic.

3.1.2 Seismic Risk Analysis of Highway Systems (Werner et al., 2000)

The seismic loss analysis procedure of Werner et al. (2000) consists of 4 modules: a System Module, a Hazards Module, a Component Module, and an Economic Module. The system module contains the data and models for the network analysis of the transportation system. Typical data includes the network configuration, number of lanes, lane capacities, origin-destination flows, etc. The hazards module includes data on soil conditions, fault locations, etc. The hazards module simulates earthquake hazard such as ground motion, liquefaction and surface fault rupture. The component module is used for calculating the losses and functionality of various components of the transportation infrastructure. It thus includes fragility and restoration curves. Finally, the economic model calculates losses in terms of increase in travel time and distance in the post-earthquake system states. The component module also calculates these system states through its restoration model.

The analysis is highly data-intensive and uses a detailed inventory of the transportation network and seismic vulnerability models to create scenarios. The hazards module simulates ground motion, liquefaction and landsliding using seismic zone, topography and soil condition data. The component model then predicts damage to the transportation network elements and their functionalities. The model also calculates traffic states for each bridge at various time intervals after the earthquake. The traffic states define the usability of the bridges, for example, "closed for repair", or "partially open". This is done by using data on typical restoration times corresponding to different damage states. The elements modeled include highway bridges, roadway pavement, and approach fills. Using this damage and functionality data for the network elements, a system state of the highway network is developed. Finally the system module carries out extensive transportation network analysis at each time step using the network states predicted by the hazard and component modules. This analysis is urban in nature (considers personal travel such as commuters, consumers, etc. besides the local freight traffic), and employs an advanced associative memory

(AM) approach[3] that can efficiently predict traffic system states given a fixed OD matrix, trip data, traffic zones, etc. The basis of the AM approach is the user equilibrium (UE) method of modeling urban flows. The user equilibrium flows works on the basic assumption that every road user tries to minimize his/her travel time for traveling from a point A to point B. Thus, an optimization procedure can be used to distribute flows knowing the OD matrix. Several simulations of UE flows in damaged states are used to *train* the artificial intelligent AM system, so it can predict the response (changes in flows) of a stimulus (damage to the transportation network), without carrying out rigorous optimization. Thus, the component module optimizes the flow of OD traffic (from the pre-earthquake state) on the post-earthquake transportation network. These transportation network flows are used to find the increase in travel times across the network and the cost associated with this increase.

The procedure can develop aggregate results that are either deterministic (consisting of a single simulation for one or a few scenario earthquakes) or probabilistic (consisting of multiple simulations and scenario earthquakes). It uses a Geographical Information System (GIS) database for network inventory and other data (such as OD flows, traffic zones) and has a user-friendly interface for most operations. The system also uses a user-friendly GIS interface to create scenarios and display results. The system will eventually be developed into a software package called REDARS to be distributed freely. A detailed scenario analysis based on this methodology has been carried out for the Shelby County, Mississippi.

The model developed in this study calculated losses that are limited to the increase in travel time. It considers the *demand* of the transportation network as exogenous and therefore does not model the damage to non-transportation infrastructure (buildings, lifelines, etc.). Thus, the losses do not include the effect of reduced transportation demand that may arise due to reduced productivity of industries in the region. Also, it does not consider the effect of limitations in the transportation network in creating shortages (or problems in shipping goods). These indirect effects

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[3] A method derived from the field of Artificial Intelligence and used for finding approximate solutions to constrained optimization problems

of the limited transportation capacity are spread throughout the economy through interactions and may result in considerable losses, but these losses are *not* captured in this analysis.

The approach is also computationally demanding and requires extensive data. These computational and data requirements of the analysis limit the scope of the methodology to a small region (urban, or a county) and requires expensive data collection for any region that has to be analyzed. The traffic components modeled are urban in nature (commuters, consumers, etc.) and the method of assuming a static OD matrix is not entirely suitable for a regional analysis. For a regional analysis, it is important to consider that commodities from different sources are largely interchangeable and the OD matrix can change under adverse situations that warrant such a change (like transportation constraints).

3.1.3 An Integrated Model of Highway Networks and the Spatial Metropolitan Economy (Shinozuka et al., 1998)

The study models the effects and the consequent losses of an earthquake on industries and the transportation infrastructure of a metropolitan region. The Los Angeles metropolitan region is considered for the models developed in the methodology.

The methodology developed in this study has an urban scale of operation and uses detailed models and inventory data for analyzing the effects of a scenario earthquake. Models and data used for the analysis include EPEDAT[4], the Regional Science Research Institute's (RSRI) 515 sector Los Angeles area Input-Output model, SCPM1[5], 1991 Southern California Association of Governments' Origin-Destination Survey data, and the interregional and international trade flows from a variety of sources, including studies by DRI-McGraw, Caltrans and the Port of Los Angeles. Using these models, effects such as direct damage and loss of functionality of industrial

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[4] The Early Post-Earthquake Damage Assessment Tool; a proprietary structural damage and industrial loss of functionality assessment tool developed by EQE International

[5] Southern California Planning Model 1; A spatial allocation model of Southern California that has been used to distribute aggregate input-output results (in $ and/or jobs) to 308 zones (political jurisdictions) across 17 economic sectors

production capacity, damage to the transportation network, changes in the spatial input-output system, changes in transportation network flows, post-earthquake OD flows, etc. are modeled. The model thus integrates the transportation system with the input-output model of the Los Angeles metropolitan area and can predict the effect of transportation constraint on the general economy. The study also includes a scenario analysis of a 7.1 magnitude earthquake in the Elysian Park blind thrust fault[6].

The study is one of the most comprehensive studies on microscopic earthquake loss estimation including transportation network affects. The transportation system is modeled explicitly in an integrated framework where the spatially distributed industries interact through commodity flows on the urban transportation network. The origin-destination matrices for freight flows can thus change after the earthquake to reflect the change in the transportation cost as well as the reduced transportation demand due to the damage to production facilities. The damage to the transportation system includes a rigorous model for bridge damage, which includes site conditions at bridge location.

However, the entire methodology is limited by its microscopic scope, data intensiveness, specificity to southern California, use of proprietary models, and the complexity of the model that makes it hard to adapt to other geographical regions. Thus the methodology cannot be applied universally or increased in its geographic scope. The model also lacks a restoration model and the losses are based on constant damage for a discrete period of time. This is a highly coarse form of representation of the time dependent post-earthquake system states as the analysis does not account for the differential recovery of the elements and the changing system state for interactions (see Section 2.3). Also, the industrial functionality prediction model lacks the interactions with lifelines and other infrastructure (including damage to residential facilities).

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[6] The Elysian Park fault is a recently-discovered blind fault beneath central Los Angeles

3.2 Earthquake Loss Estimation Models Not Including Transportation Network Damage

There are a few state-of-the-art methodologies for generalized earthquake loss estimates that do not include transportation network damage. Much of the literature in this category is proprietary and is used extensively by insurance firms to assess exposure of their portfolios. Risk Management Solutions' (RMS) Insurance/Investment Risk Assessment System (IRAS) and EQE's EPEDAT are classic examples of these proprietary risk analysis systems.

HAZUS[7] (National Institute of Building Sciences, 2000a) is one of the very few comprehensive earthquake loss systems available in the public domain.

HAZUS has been developed by Federal Emergency Management Agency (FEMA), under a Cooperative Agreement with the National Institute of Building Sciences. It is an extensive, nationally-applicable methodology for assessing earthquake risk. Figure 3-1 summarizes the various loss elements modeled in the system.

HAZUS includes direct physical damage, induced physical damage, direct economic/social loss and indirect economic loss and relies on extensive infrastructure inventory for the analysis. The direct economic losses modeled include losses due to damage to building stock, bridges, lifelines, etc., and the losses due to the effect of limited functionality of industies and lifelines. The indirect losses include losses from industrial interactions ("ripple effect") of constrained industries[9]. The inventory includes building stocks (for industries, commercial sector, residential, etc.), lifelines, transportation infrastructure, essential facilities, etc. The restoration of each element is modeled explicitly through restoration curves. The user-friendly Geographical Information System (GIS) system can be used to create a scenario earthquake and calculate various losses.

The earthquake loss estimation methodology is an improvement over existing re-

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[7] HAZUS ®stands for "Hazards U.S."

[8] Source: HAZUS technical manual (National Institute of Building Sciences, 2000a)

[9] The classification of direct and indirect losses differs from the system used in this methodology; refer to Section 2

gional loss estimation methodologies, since it more comprehensively addresses regional impacts of earthquakes that have been omitted or at best discussed in a qualitative manner in previous studies. Examples of these impacts are service outages for lifelines, estimates of fire ignitions and fire spread, potential for a serious hazardous materials release incident, and indirect economic effects (from interactions in the economy). These indirect effects are calculated through an advanced input-output analysis model, which includes inventory levels of commodities, supplemental imports, employment levels, etc.

The system however lacks the ability to perform a transportation network analysis. Thus the transportation-related losses are limited to direct damage to the network inventory and indirect losses due to network constraints are not included. This implies that several of the losses that come from constrains in the transportation system have not been modeled and the network is essentially treated as invulnerable (or having sufficient redundancy) for the purpose of indirect loss analysis. Nevertheless, the system uses advanced engineering earthquake risk models, vulnerability models, economic interaction models and collects extensive inventory data and is by far the most comprehensive earthquake risk estimation methodology developed.

Table 3.2 compares various features of the studies discussed above with the methodology developed in this thesis.

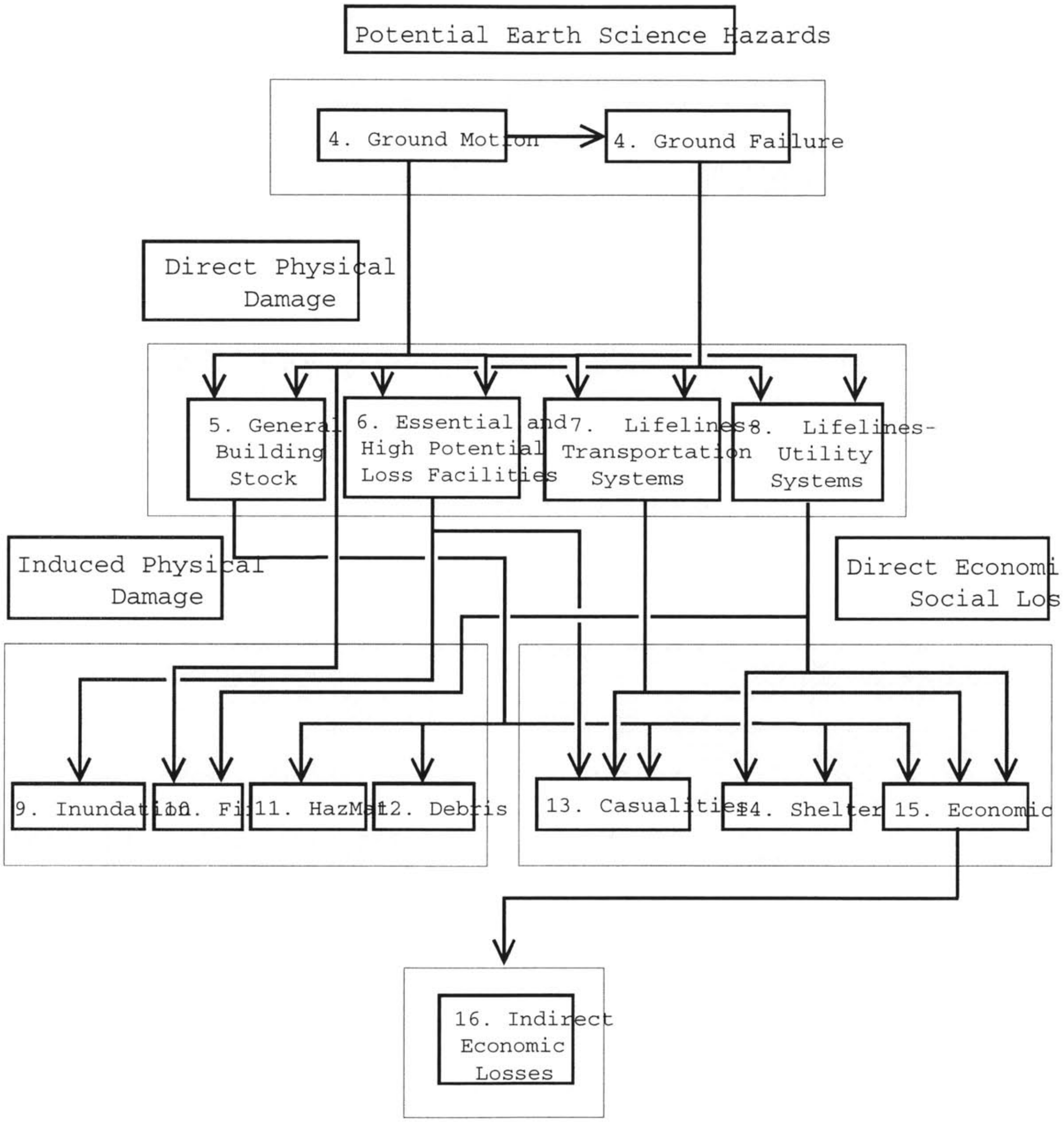

Figure 3-1: HAZUS Earthquake Loss Estimation Methodology[8]

	HAZUS	**Werner et al.**	**Shinozuka et al.**	**Kim et al.**	**Methodology developed in this thesis**
Geographical Scale of operation	Regional, applicable to the whole U.S.	Metropolitan, applicable to any urban region	Urban, specific to L.A. metropolitan area	Regional, applicable to the whole U.S.	Regional, applicable to the whole U.S.
Detail in transportation network	None included for transportation network flow modeling	Detailed inventory of urban road system	Detailed inventory of L.A. region roads	Interstate network abstracted for analysis	Actual interstate network; detailed in region of direct impact
Infrastructure earthquake vulnerability	Yes, for most structural components including transportation infrastructure	Yes, for highway bridges, approach fills, and roadways	Yes, explicitly modeled for highway bridges & industrial seismic performance	No, hypothetical scenario	Yes, for building stock, lifelines, highway pavements and bridges
Recovery of components	Yes, detailed recovery models	Yes, for highway components only	No, post-earthquake damage state assumed constant for a year	No	Yes, explicitly modeled
Direct Losses	Yes	Yes, only for highway components	Yes	No	Yes, for building stock, highways and bridges
Indirect Losses (Business Interruption Losses)	Yes, not including transportation-related effects	Yes, limited losses based on increase in travel time	Yes	Yes, through input-output models and increase in travel cost	Yes, through input-output models and increase in travel cost
Industrial interactions (through input-output models	Yes, detailed input-output modeling for indirect losses	No, transportation demand is thus exogenous	Yes, detailed input-output models	Yes, input-output models for industrial interactions	Yes, input-output models for industrial interactions
Predicts Network Flows	No, no transportation flow models	Yes, detailed artificial intelligent approach	Yes, urban transportation planning method	Yes, optimization algorithms minimizing transportation costs	Yes, optimizing transportation network costs
Freight/Travelor	None	Both	Both	Freight	Freight
Indirect losses in transportation network	None	Increase of travel cost	Increase of travel cost and affect on economy	Increase in travel cost and affect on economy	Increase in travel cost and affect on economy

Table 3.2: Comparison of various approaches

3.3 Microscopic Studies on Earthquake Risk and Hazard

The scope of the methodology includes earthquake vulnerability of several components (building stocks, lifelines, inter-regional transportation network). Thus, a brief discussion of these engineering and studies is also warranted.

Applied Technology Council's ATC-13 (Applied Technology Council, 1985) is a notable report on earthquake vulnerability of structures. The report presents expert-opinion earthquake damage and loss estimates for industrial, commercial, residential, utility and transportation facilities in California. Included are damage probability matrices for 78 classes of structures and estimates of time required to restore damaged facilities to pre-earthquake usability.

The report also describes the inventory classification information essential for estimating economic losses. Even though the results were developed specifically for California, the results of the study are universally applicable with slight modification.

The ATC-13 is the de-facto source for damage curves, functionality relationships and inventory classification. Researchers have traditionally used ATC-13 as a knowledge base to developed methodologies or improve on the literature. Improvement and additions to the ATC-13 literature is needed in light of new developments and requirement of integrated methodologies like the one presented in this thesis. For example, restoration curves in ATC-13 are non-analytical and are based on expert opinion. Restoration functions can however be viewed as a function of resources and technology used to rebuild the structure. A review of literature concluded that such analytical functions have not been investigated by researchers yet.

There are several other microscopic engineering studies that concentrate on a class of infrastructure, or a particular structure. These microscopic studies are helpful in understanding the individual element performance and aggregate seismic behavior.

It is clear from the review of the literature that contemporary earthquake loss analysis methodologies have lacked in terms of developing an integrated, comprehensive methodology, where all the effects of an earthquake and economic loss components are modeled together. The studies usually focus on a *part* of the problem, emphasizing aspects such as earthquake vulnerability of elements (direct losses due to damage of structures), effects of a damaged transportation network (through increase in travel time, or restrictions in commodity flows between regions) or a small geographical region (like a county or an urban area). As emphasized in Chapter 2, it is important to have an integrated approach where interactions and all components of loss are modeled on a geographical scale that encompasses all these losses.

The next chapter describes the methodology developed for estimation of earthquake losses that attempts to address some aspects not satisfactorily modeled in these methodologies. As is obvious from the broad and interdisciplinary scope of such a methodology, the analysis has several simplifications when compared to the contemporary studies. However, an attempt has been made to develop a framework that is comprehensive, allowing for better models and higher resolution to be integrated within the methodology.

Chapter 4

Proposed Methodology for Estimation of Earthquake Losses

4.1 Introduction: Basic Framework

This section introduces the proposed earthquake loss estimation methodology. The section is divided into two parts: the first part introduces the organization of the model, including data and geographical layout; the second part gives a brief overview of the analytical framework. Components and models mentioned in this section are discussed in detail in Section 4.2.

4.1.1 Physical Model Layout

The model operates on a macroscopic scale and covers the entire U.S. The U.S. is divided into several regions for the analysis. These regions will serve as "nodes" in the analysis, connected by a system of transportation "links" for modeling interregional commodity flows.

Figure 4-1 shows the major cities (population $\geq 10,000$) and major highways of the U.S.. It can be observed that most of the regions with high population density are concentrated around the intersections of highways. Therefore, for simplicity, a fair approximation is to consider these intersections as *nodes* for the analysis. The nodes (or a subset of these nodes) can therefore be used to aggregate infrastructure and economic activity around these points in geographical space.

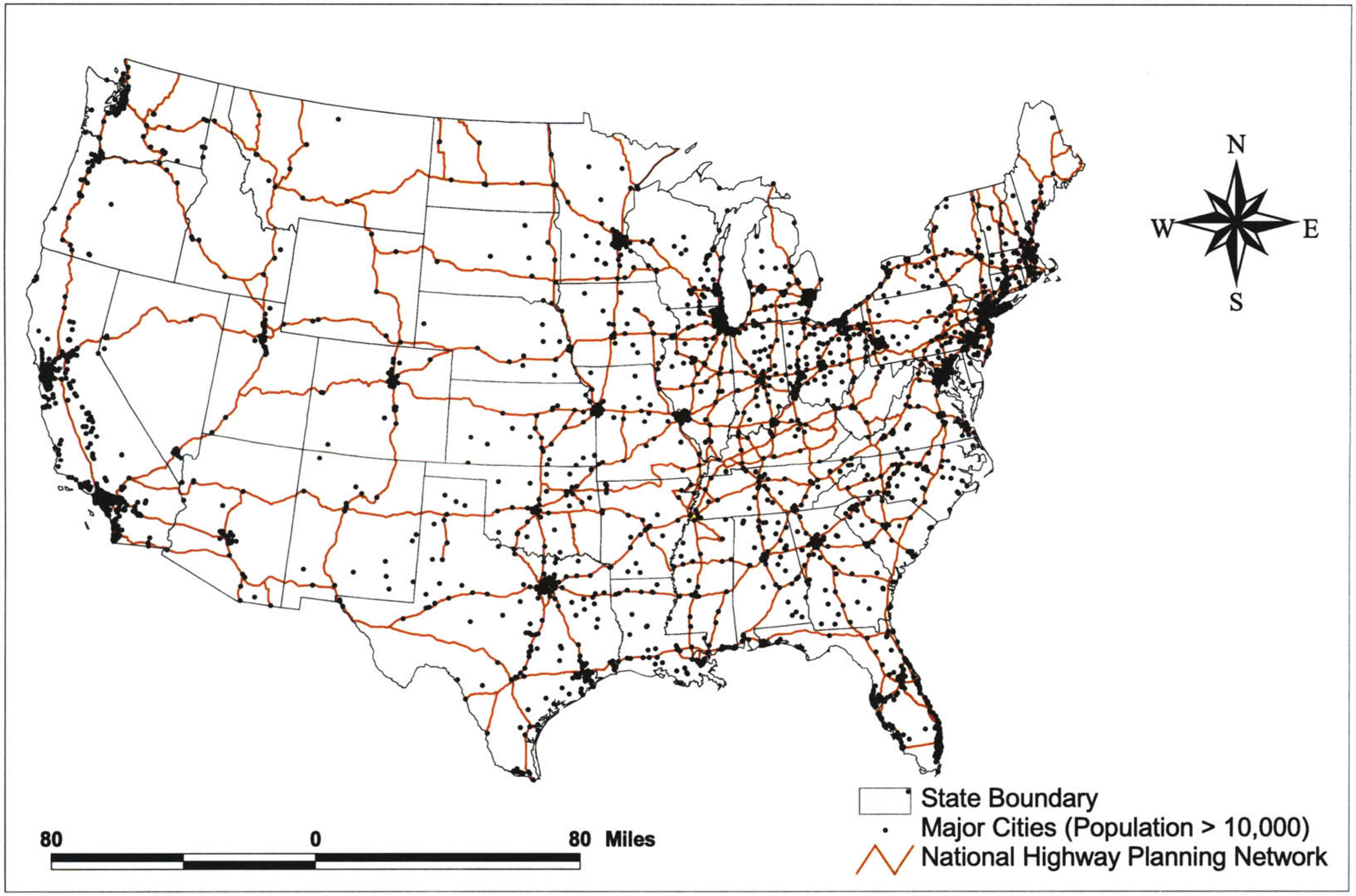

Figure 4-1: Distribution of Major Cities and Highways

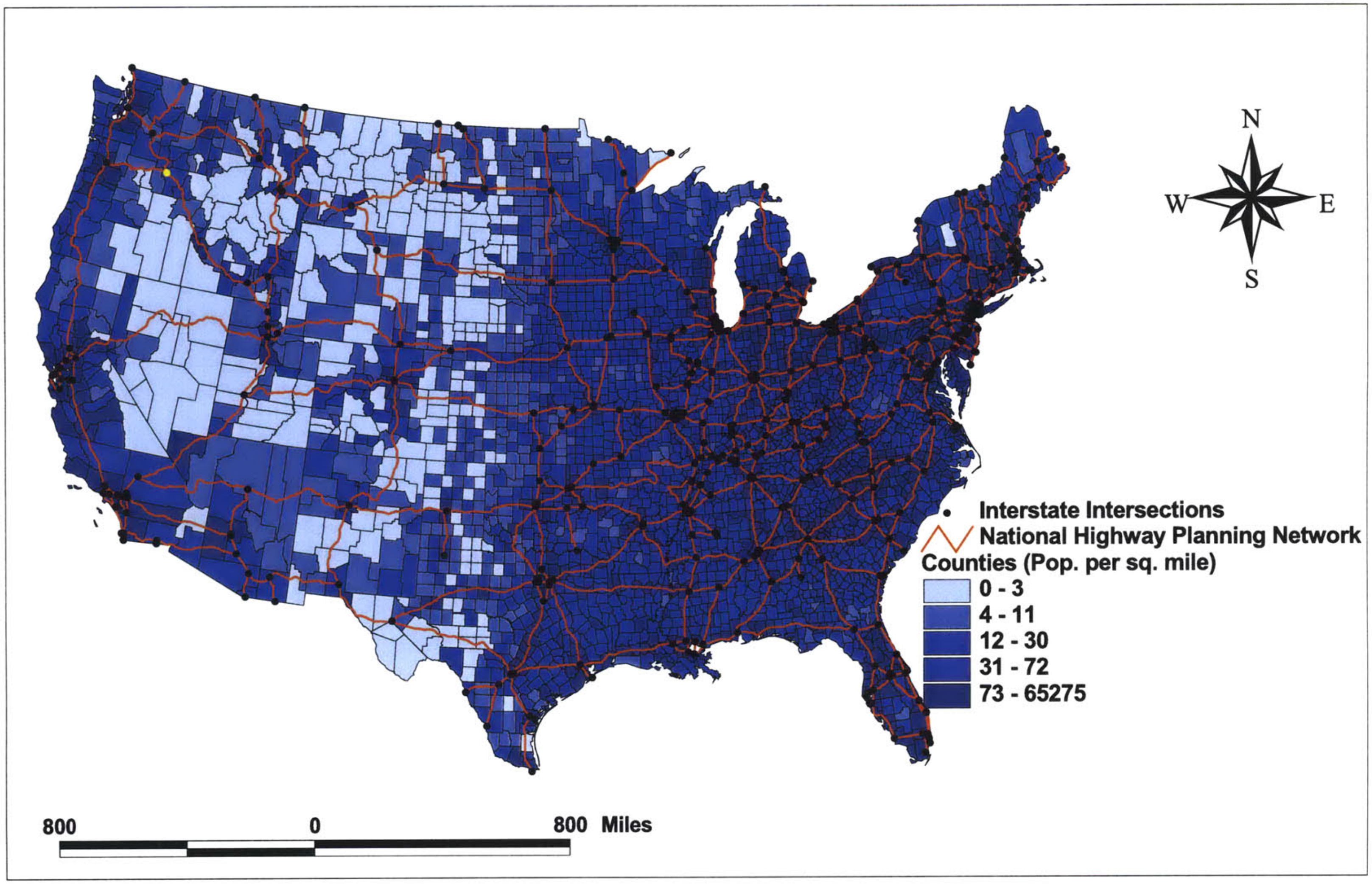

Figure 4-2: County population density and the National Highway System

Counties can be used as the lowest unit of area to be associated with each node. A *closest node analysis* of the centroids of counties with respect to nodes provides us with an association of each county with nodes. Thus, all counties associated with a single node form a region, and will be assumed to have uniform characteristics for the analysis. This aggregation and simplification is necessary to reduce resolution and thus achieve computational feasibility and consistency with data availability (see Section 2.2).

The nodes of the network are composed of 13 economic sectors, and the residential, lifeline and transportation sectors. Of these, 9 earthquake vulnerable economic sectors and the residential sector can be mapped on to 7 *occupancy classes.* The occupancy classes are used as an intermediate step for associating economic sectors with fragility models.

The occupancy classes are composed of several *structural classifications* for the purpose of vulnerability modeling. To exemplify this 2-stage mapping, the "fabricated metals industry" is an economic sector that can be mapped on to the "heavy industrial" occupancy classification. The heavy industries in-turn can be composed of some buildings of reinforced masonry type construction, and others of heavy steel type construction. Some economic sectors are treated as invulnerable to earthquakes (such as the "mining industry") and cannot be mapped onto any occupancy class. The transportation infrastructure on nodes and lifeline infrastructure components directly map onto their respective individual vulnerability models.

Such a system of classification was necessary to be able to use existing data and models for fragility as well as economic modeling. The 13 economic sectors were suitable for modeling of the input-output system and commodity flows, whereas the fragility classification is based on the structural composition of the facilities. Table 4.1 describes the various sectors considered and its mapping on to the fragility class across the occupancy classes.

The node data also describes the total built-up area on the node for each of these occupancy classes. An abstract indicator of lifelines and transportation infrastructure content is also associated with each node.with fragility

The highway sections connecting this system of nodes are considered *links* for our analysis. Each of highway sections is bounded by nodes (or intersections) and can be represented by 2 unidirectional links. For all practical purposes, each direction of the highway can be considered independent of the other[1]. Thus, each highway section is represented by two links (one in either direction) and each link of the analysis is unidirectional. This system of dual representation of highway sections is suitable for performing a network analysis that requires a directed network[2].

The links have details about the total length, lanes in each direction, and all bridges on it. The bridges are further divided by construction type for the purpose of vulnerability modeling. A network with nodes connected by abstracted links is thus obtained.

The travel cost associated with the links in this abstracted network are assumed to be directly related to the length of the sections. A more complex, capacity and congestion based cost function is beyond the scope of this work, but can be added with further work on the models. The capacity of the link is dictated simply by the number of lanes on each section in the pre-earthquake situation. The capacity of each directed individual link is calculated as the minimum functionality of the bridges in the post-earthquake state. This is a reasonable assumption as the capacity of a highway section is decided by the most constrained section.

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[1] For vulnerability modeling, a bridge that carries traffic in both directions can be considered as one, and finally disaggregated into 2 unidirectional bridges of half the capacity for loss of functionality calculations.

[2] A network in which all links in the network have a unique direction

Sector	Economic Sector Code	Occupancy Class	Fragility Classification
Building Stock			
Agriculture, Forestry and Fisheries	1	-none-	-none-
Mining	2		
Construction	3		
Food and Kindred Products	4	Food & Drug	Each class composed of: Unreinforced Masonry(UM), Reinforced Masonry(RM), Reinforced Concrete(RC), Light Steel (LS), Heavy Steel (HS) and Timber
Chemicals and Allied Products	5	Chemical (CHEM)	
Primary Metals Industries	6	Heavy Industry (HI)	
Fabricated Metal Products	7	Heavy Industry (HI)	
Industrial Machinery and Equipment	8	Heavy Industry (HI)	
Electronic and other Electric Equipment	9	High Technology (HiTech)	
Transportation Equipment	10	Heavy Industry	
Other Non-durable Manufacturing	11	Light Industry (LI)	
Other Durable Manufacturing	12	Light Industry (LI)	
Service, and Government Enterprises	13	Commercial (COM)	
Residential	-	Residential (RES)	
Other Infrastructure			
Transportation	-	-none-	Transportation
Lifelines	-		Lifelines

Table 4.1: Node Infrastructure Classification System[3]

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[3] Industrial/Commercial classification source: Okuyama et al. (1999); Occupancy and fragility classification source: Applied Technology Council (1985)

4.1.2 Analytical Framework

The analytical framework of the methodology is summarized in Figure 4-3. The analysis initiates with a simulation of an earthquake. Parameters for the scenario earthquake include epicentral intensity and the epicentral location. An ***attenuation model*** is used for the calculation of ground shaking intensities at various nodes and bridges in the network. Thus, bridges and nodes closer to the scenario epicenter will experience higher ground shaking intensities and these structures will be affected more.

The ground shaking intensities are then used by the ***fragility model*** to predict the level of damage to each occupancy class (residential, commercial, and industrial classes) and the lifelines and transportation infrastructure on the node. Each of these occupancy classes is further composed of several structural classifications for vulnerability modeling (e.g., timber, reinforced masonry, etc.). Fragility curves of structural classifications are then used to analyze the weighted damage to each occupancy class. Similarly, each bridge on the interregional transportation links corresponds to a vulnerability classification. A bridge fragility model is used to calculate the damage to the highway bridges. Highway pavements are modeled using a single vulnerability classification and can be directly analyzed for damage.

A ***restoration-interaction*** model calculates the initial functionality of each of the 9 occupancy classes and links. As noted before, each of the earthquake-vulnerable economic sectors maps onto an occupancy classification. Thus, the final functionalities of the corresponding occupancy class is used to obtain the productivity of the economic sectors.

A minimum functionality criterion determines the functionality of the links. The overall functionality of a link is calculated as the minimum of the functionalities of all bridges and the highway pavement itself. Thus, if a link has several bridges and the bridge with lowest functionality is 50% operational, the capacity of the link is reduced to 50%. This is a reasonable assumption, as that bridge will be the constraining factor creating a bottleneck in the link.

The functionalities of economic sectors, residential, transportation and lifeline infrastructure on the nodes are further affected by the functionality of other facilities. For example, functionality of an economic sector producing high technology commodities is reduced by the limited functionality of lifelines such as electric-power networks. Functionalities of economic sectors can therefore be constrained by the limited functionality of other supporting infrastructure such as lifelines. These new constrained functionalities are also modeled in the restoration-interaction model.

The production levels of an economic sector can be directly related to its functionality. Therefore, a functionality of 50% implies a maximum production level of 50%. The constrained functionalities of the economic sectors (after the interactions) are used to calculate the these production levels of economic sectors. Thus, the maximum damage-constrained production levels can be obtained.

Reduced production levels for the nodes however ignore the reality that economic sectors may not operate at their capacities. Further, other factors such as inventory levels, foreign imports, alternate sources, etc., can buffer the effect of reduced functionality. Modeling all of these is beyond the scope of this thesis; therefore, a simplified approach is adopted wherein production levels across the region considered (both within, and beyond the region of direct impact) are increased uniformly to balance the deficit created by the damaged nodes using a ***global input-output optimization model***. The model puts constraints on the maximum possible increase of functionality of each economic sector. Thus, multiplicative factors are obtained that can be applied to the pre-earthquake functionalities of each economic sector on all nodes in the analysis, signifying an overall increase in the productivity levels across the region considered to account for the deficit created by the earthquake.

A ***local (nodal) input-output model*** is used to find the balance of commodities produced by each economic sector and consumed by other economic sectors (intermediate demand), and the population (final demand) within the node. These values determine the levels of imports or exports of each of the 13 commodities produced by the 13 economic sectors on each node.

The analysis now deals with the spatial interaction of industries through the interregional transportation system. Ideally, the process of optimizing flows on the network and the import/export from the nodes should be performed simultaneously. However, due to the extremely large and complex nature of solving this problem, a two-step iterative solution approach is used. In the procedure, network optimization and node balancing is done iteratively until all nodes are balanced.

The nodal import-exports are supplied to the ***network model*** for finding the optimum flows on the network. The network flow model optimizes the flow of commodities[4], minimizing the total cost of transportation across the network, while respecting the capacity constraints on each link and the node balance constraints. The network is constrained in its capacity by the inherent maximum flow possible (number of lanes) and further by the damage to the links, causing either an increase in the total travel time on the network, or making certain flows infeasible (if all links to access a particular node are impassable or at capacity).

We now have the optimal flows on the network wherein imports and exports are redistributed among the nodes using a minimum cost criterion. The imports and exports are thus satisfied by the closest available source of those commodities. If the imports and exports that are deemed feasible by the network model are consistent with the node requirements, the node is assumed to be balanced or satisfied. However, this may not always be possible, as shortages on the global scale or transportation constraints will produce deficits or surplus of commodities on certain nodes. Physically, this means that the particular node requiring a certain amount of a commodity will not be able to source it from other nodes because of a global shortage, or because the node is inaccessible.

If the node is not balanced and has a deficit/surplus of a particular commodity, the *local input-output model* is used to balance the node internally. The node-balancing algorithm tries to achieve maximum production and consumption levels for each commodity, given the limited imports and exports. However, if the node

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[4] Passenger flows have not been modeled in the methodology, and it is assumed that these flows on the inter-regional transportation network are minimal relative to the freight flows. Further work on the methodology can include models for passenger flows.

cannot be balanced, ideal adjustments to production levels and consumptions are made to comply with the real import/exports. New values of these imports/exports are then again supplied back to the network model for transportation flow modeling. The network will now produce new values of feasible imports and exports for each node and the process of balancing the unsatisfied nodes is repeated until all nodes are found feasible. Though it is not intuitive that such an algorithm will converge, experimentation with the model displayed fair amount of convergence and reduction in number of infeasible nodes with each iteration. Thus, the procedure is repeated until all nodes are feasible and balanced.

The methodology explicitly considers recovery of elements. Thus, the system state continuously changes after the earthquake until the system restores full functionality. The *interaction-recovery* model is used for calculating the functionalities of each economic sector and infrastructure at discrete time-steps after the earthquake. The whole process of global optimization, and iterations of network and node balancing is repeated for the new system state. Finally, losses at each time step are aggregated until the complete functionality of all elements is restored (or until the time when the functionality reduction is minimal).

The next section discusses the models used in this analysis in detail.

4.2 Components

The various components of the methodology as illustrated in Figure 4-3 and referred to in Section 4.1 are described below. As discussed before in Chapter 2 and Chapter 3, the broad scope of the methodology, limited computational resources, and unavailability of data and models necessitated several simplifications and omissions. However, as better models, computational resources and data become available, they can be integrated in the methodology. The methodology is also highly "modular", implying that components detailed below are not hard-wired into the methodology and can be replaced with better models when they become available.

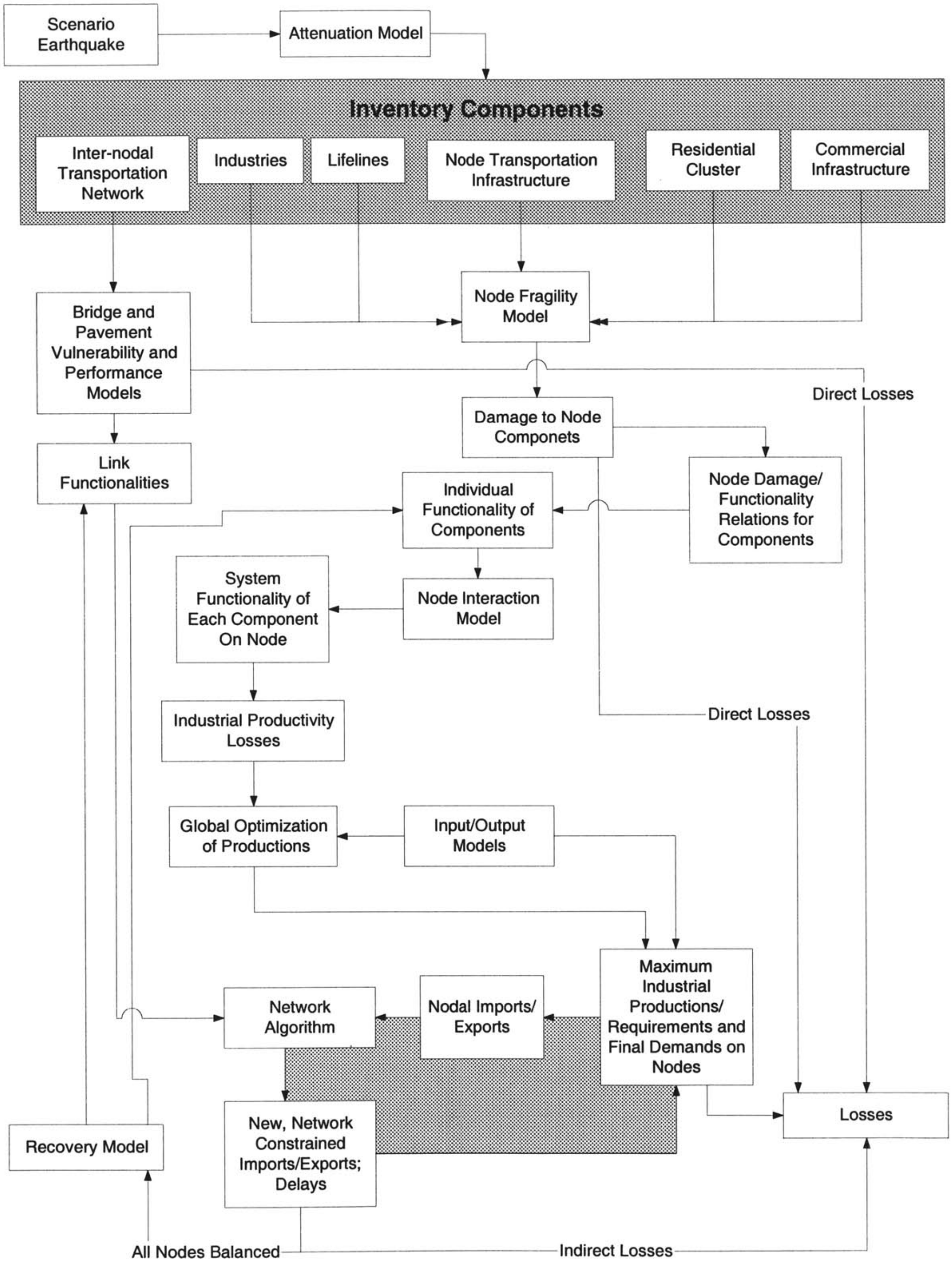

Figure 4-3: Summary of the methodology

4.2.1 Attenuation Model

The attenuation model calculates the intensity of an earthquake at any point as a function of earthquake characteristics and geologic conditions and distance from the earthquake epicenter. There are several complex models that take into account the local geology (for example, site conditions, etc.) and other characteristics of the earthquake (for example, depth of the earthquake epicenter). However, these models require extensive local site data and are beyond the scope of this thesis.

The model calculates the intensity using the *Bollinger attenuation function.* The model predicts the intensity on the Modified Mercalli Intensity[5] (MMI) scale as a function of the distance from the earthquake. Further, the fragility models are based on this scale of ground shaking.

Intensity of the earthquake is given by the following equation:

$$I_d = I_{epi} + a - b * D - d * \log_{10}(D + 10); \qquad (4.1)$$

where:

I_d: the intensity of ground shaking at point d

I_{epi}: the intensity of ground shaking at the epicenter of the earthquake

D: the distance of the point d from the epicenter in kilometers

The coefficient of the Bollinger equation:

$a = 2.87$

$b = 0.00052$

$d = 1.25$

The human perceptibility and the damage caused by ground shaking of various intensities are described in Table 4.3.

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[5] Modified Mercalli Intensity is a measure of local ground motion severity due to an earthquake. It is a scale ranging from I (1) to XII (12), where XII is the most severe ground shaking.

I	Not felt except by a very few under especially favorable conditions.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Table 4.3: MMI intensity scale and damage (Source: USGS website; www.usgs.gov

4.2.2 Seismic vulnerability model

Earthquake direct loss can be express through fragility curves. A fragility curve, in its most commonly used form, displays the probability that a structure is damaged beyond a specified damage state at various levels of ground shaking. The curves used in this methodology are deterministic and do not account for the fact that, there can be considerable variation of seismic performance for a given intensity of ground shaking. Thus, all structures of a particular structural class are assumed to be damaged to the same level for any earthquake affected node. This assumption was necessary for simplicity of the models, however further work will incorporate uncertainty in damage analysis. Sensitivity analysis of losses to uncertainty will be used to assess the inaccuracy introduced by such an assumption and suitable models incorporated.

Equation 4.2 defines the *damage factor*, which is used to represent the fragility of structures (Applied Technology Council, 1985).

$$Damage\ \ Factor\ (DF) = \frac{Dollar\ \ Loss}{Replacement\ \ Value} \tag{4.2}$$

Knowing the intensity of ground shaking at a point, damage to building stock and infrastructure classes can be derived based on the fragility of the structural class. Besides the economic interpretation of damage factor, the factor is also an indicator of physical damage to any structure and can be used for deriving functionality loss as a result of damage.

The fragility models classify the structures based on their structural characteristics. The curves as well as the classification system used in this methodology have been obtained from Kunnumkal (2001a). The primary reference for Kunnumkal (2001a) is the ATC-13 (Applied Technology Council, 1985) document. However, ATC-13 has a detailed classification of the building and other infrastructural classes. The study classifies all structures into 78 different structural classes. Out of these, building stock is disaggregated into 40 classes, while the rest are classifications of highway components (bridges, pavement, etc.), lifelines, etc.

For the purpose of this analysis, a simpler, coarser classification of structures based on the structural features is used. The next section describes the building classification used in this methodology.

Building structural classification

1. **Unreinforced Masonry(UM)**

   Structures of this type have walls constructed of cut stone, solid brick, masonry or solid brick units stacked together with mortar. Walls of this type of construction lack adequate steel reinforcement.

2. **Reinforced Masonry(RM)**

   Structures of this type have walls constructed of masonry units stacked together with mortar, brick, concrete block, hollow clay tile or other masonry shear walls, fully reinforced both horizontally and vertically with steel reinforcing bars.

3. **Reinforced Concrete(RC)**

   These structure have ductile moment resisting frame. Beams and columns have especially designed steel reinforcing to resist collapse even when concrete is heavily damaged.

4. **Light Steel (LS)**

   Such construction uses light metal frame, prefabricated beams columns and joints. Exterior walls are often made of metal or asbestos-cement panels bolted to the frame, and the roof is typically corrugated metal or fiberglass.

5. **Heavy Steel (HS)**

   Structure of this type have steel moment resisting frame. The beam-column joints transmit bending between beams and columns in such construction. Exterior walls can be metal, precast concrete panel or brick masonry.

6. **Timber**

Such construction uses light wood stud walls, wood frame made of plywood sheet or wood planks. The roofs and floors are made of plywood or planks and supported by wood walls and columns.

7. **Lifelines**

   Lifelines include electricity-power distribution networks, water networks, oil & gas distribution networks, transportation infrastructure on nodes, etc. The methodology is very coarse in its representation of the lifelines. Each lifeline can be considered individually and system effects modeled in detail. However, at this time, considering each lifeline is not feasible because of the macroscopic level of operation of this methodology. Further work will attempt to disintegrate each lifeline and develop individual models for earthquake vulnerability.

8. **Transportation system**

   The transportation system considered in this methodology is distributed in two components: the node-based transportation infrastructure (covered above in lifelines), and the inter-node highway network.

   The methodology does not model the node-based transportation system in detail. Instead, an indicator of the transportation infrastructure content on the node is used for finding the damage to this component and the associated functionality losses.

   The inter-nodal highway network considered for earthquake vulnerability modeling includes the highway pavement and the bridge components. Highway pavement can be damaged by ground shaking requiring repair. The damage can also reduce the usability of the highway section due to broken pavement and reconstruction efforts. Bridges can be damaged by earthquakes and usually need heavy resources and extended periods of time to be repaired.

   All highways are considered to have similar earthquake vulnerability (fragility curves) for the methodology. This is a reasonable assumption as the construction types of most highways is similar.

The earthquake vulnerability classification system for the bridges is enumerated below:

(a) *Conventional*

Conventional bridges consist of multiple simple span bridges and continuous/monolithic bridges. Conventional bridges are defined by ATC-13 as having a span of less than 500 *feet*.

(b) *Major Bridges*

Major bridges are bridges with a span greater than 500 *feet*.

Again, this is a very coarse classification for fragility modeling. A detailed model for bridge vulnerability can be included with the availability of fully developed generalized models that can be applied to all bridges under consideration.

The fragility curves used for all structural classes are normal cumulative distribution functions. Table 4.4 gives the parameters of the fragility curves for the respective structural classes. These parameters (mean and standard deviation) are used to obtain the fragility curves for each class.

The distribution function is given as:

$$Damage\ Factor(I) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{I} e^{\frac{-(x-\mu)^2}{2\sigma^2}} dx \tag{4.3}$$

where:

I: the intensity of ground shaking at the node or coordinate under consideration.

σ: the standard deviation of the normal distribution

μ: the mean of the normal distribution

Figures 4-4 and 4-5 give the curves of the building stock and highway components respectively prepared from Table 4.4.

Facility Class	**Mean**	**Standard Deviation**
Unreinforced Masonry	8.94	1.68
Reinforced Masonry	10.49	2.03
Reinforced Concrete	11.54	2.45
Light Steel	11.93	2.34
Heavy Steel	11.73	2.3
Timber	11.7	2.45
Utilities-Electrical Transmission Lines	14.04	3.03
Roads	13.6	2.82
Bridges Multiple Simple Span	9.87	1.53
Bridges Continuous/Monolithic	10.67	1.33
Major Bridges	11.63	1.33

Table 4.4: Summary of fragility curve parameters used in the model

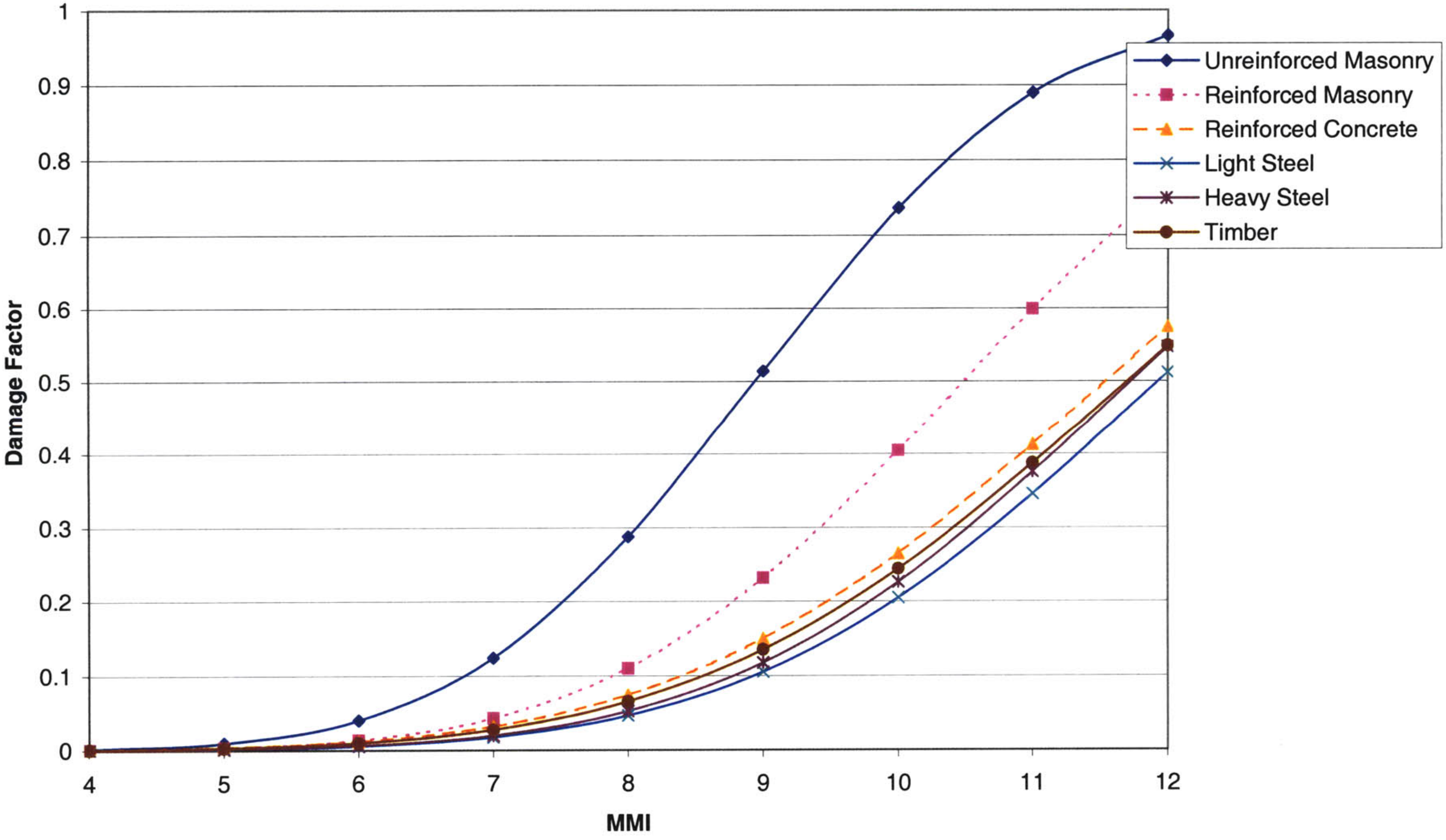

Figure 4-4: Fragility curves for building stock

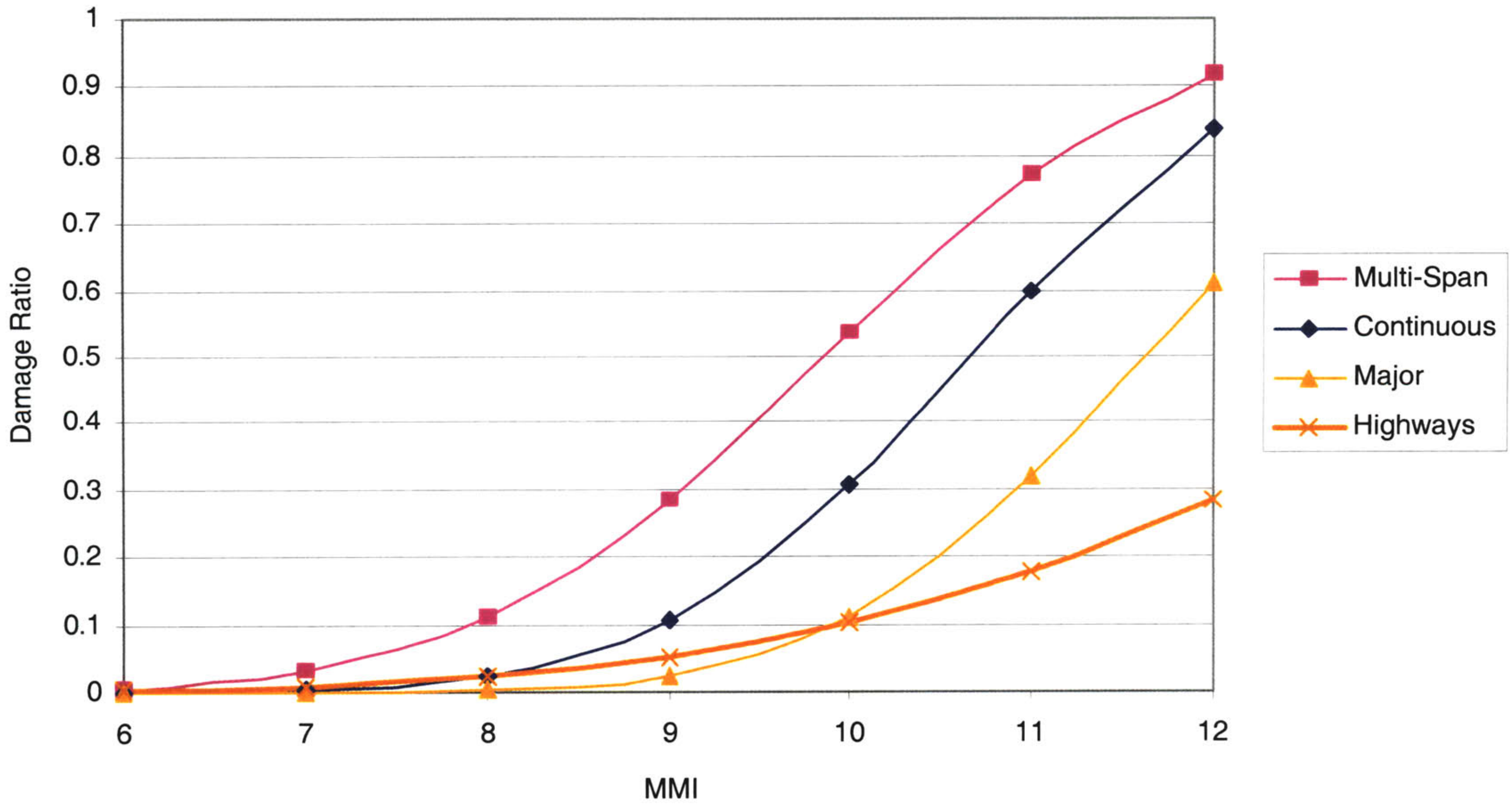

Figure 4-5: Fragility curves used for highway components

Occupancy Classification

Besides the facility classification based on the construction type, facilities can be classified on the basis of *occupancy class.* This classification is used for calculating the damage to the "contents" of these facilities as well as functionality-loss of that occupancy class. Contents include non-structural items, such as machinery in an industry, or domestic appliances. Earthquakes can damage structures, as well as the contents directly through ground-shaking (for example, overturning of domestic furniture or instrument damage), or due to structural collapse on the contents.

Each of the structural facilities described in Section 4.2.2 can be used by various occupancy classes (e.g., parts of both residential and commercial sectors may fall under the "timber" facility classification.). However, content damage, or damage to an economic sector is based on occupancy classes (e.g., residential, or the chemicals industry) and not the structural class directly. Thus, it is necessary to have another classification system that can be used for loss of functionality of economic sectors and contents damage.

The occupancy based classification system has been taken from Kunnumkal (2001a) and broadly includes all economic sectors that are earthquake vulnerable. The major source of Kunnumkal (2001a) is the ATC-13 (Applied Technology Council, 1985) study. The various classes are:

1. **Residential (Res)**

   This occupancy class consists of permanent, temporary and group institutional housing.

2. **Commercial and services (Com)**

   The commercial and services occupancy class is made-up of professional, technical and business services such as retail business, consultancy services, etc.

3. **Chemical (Chem)**

   This industrial sector produces chemicals, such as fertilizers and agricultural chemicals, food chemicals, plastics and rubber, drugs, soaps, etc.

Class	UM	RM	RC	HS	LS	Timber
Res	28	8	7	0	0	58
Com	28	9	7	19	11	26
Chem	27	17	16	19	11	10
HI	5	12	13	45	25	0
LI	27	17	16	19	11	10
F&D	27	17	16	19	11	10
HiTech	28	16	16	19	11	10

Table 4.5: Distribution of floor area by occupancy classes

4. **Food and Drug (F & D)**

   The food and drug industry includes food-manufacturing plants, tobacco manufacturers, cooking oils, beverage plants, etc.

5. **Heavy Industry (HI)**

   The major industrial manufacturing units include pulp and paper mills, steel plants , aircraft and automobile plants, etc.

6. **Light Industry (LI)**

   The light industry produces *light products* such as textiles, office equipment, electrical equipment, etc.

7. **High Technology (HiTech)**

   The high technology industries produces electronic components such as semiconductors, computing equipment, etc.

Table 4.5 (Source National Institute of Building Sciences (2000a)) describes the composition of each of these occupancy classes in terms of the structural classification. For example, if a node has a 100 units of commercial sector (Com) infrastructure, it will be assumed that 28% of it is un-reinforced masonry construction, 9% is reinforced masonry, and so on. This distribution of structural type within each occupancy class is assumed uniform over the entire U.S.[6].

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[6] Or the area influenced by the earthquake, as this data is only required for direct loss analysis

For the calculation of damage to a certain sector from an earthquake, the sector can be disaggregated by structural classification and the damage to each of the constituents obtained deterministically by using the fragility curves. The damages can be weighted for the purpose of overall damage and functionality calculation.

Value of Contents: The methodology assumes that the value of contents for all facilities is 1.5 times the total building replacement cost. The factor of 1.5 is a conservative envelope of the estimates from the ATC-13 study (Kunnumkal, 2001a), which has more detailed estimate of the value of contents. Thus, if a heavy industry building with a replacement cost of A dollars has a damage factor of 0.5, the building will require $A/2$ dollars to repair, and 1.5x$A/2$ for replacing/repairing the contents.

4.2.3 Interaction-recovery model

The maximum functionality (unconstrained by interactions with other infrastructure and economic sectors) of any sector at any time t after the earthquake is a function of the initial damage it suffers from the earthquake, and its rate of recovery. However, actual functionality and the rate of recovery of any sector are constrained by the functionality of other sectors and infrastructure. For example, the functionality of an industry depends on the availability of essential lifelines; a high technology industry may not be functional without the availability of electricity. Similarly, *recovery* of any industry depends on the functionality of transportation infrastructure on the node; with accessibility problems to construction equipment, the reconstruction efforts for the industrial sector may be hampered.

This section is divided into two sub-sections: the first part presents simple models to obtain functionality without interactions, while the second refines these model to include the effect of interactions on the functionality and the rate of recovery.

Initial functionality and unconstrained functionality/restoration at any time t

The methodology models the functionality of the industries, lifelines, residential, commercial, and the interregional transportation network at any time t after the earthquake.

For each of the occupancy classes and infrastructure classes (lifelines, node transportation, and inter-node transportation systems), the independent functionality of the element i at time t is given by Kunnumkal (2001b):

$$F_{i,nointer}(t) = at^b + c(D) \quad 0 \leq F_{i,nointer}(t) \leq 1 \tag{4.4}$$

where:

$F_{i,nointer}(t)$: functionality of class i at time t days after the earthquake (without interactions)

a, b: parameters that control the rate of recovery

$c(D)$: parameter that depends on the initial damage

Thus, the rate of recovery is controlled by the coefficients a and b. $c(D)$ also controls the time of recovery. For a given a and b, a smaller (or negative) value of $c(D)$ will result in a greater time to recover functionality to pre-earthquake functionality. A negative value of $c(D)$ signifies that the functionality of the element is 0 immediately after the earthquake (factor at^b is 0 at $t = 0$).

The dependence of the factor $c(D)$ on the initial damage is given by:

$$C(D) = c_0 + c_1 * D + c_2/D \tag{4.5}$$

where:

c_0, c_1 and c_2: parameters which are estimated from a least square fit with ATC-13 data (Kunnumkal, 2001b).

D: the damage factor from the fragility model.

The recovery parameters for the 10 classes of structures considered in this methodology are listed in Table 4.6. Figure 4-6 shows a typical functionality restoration

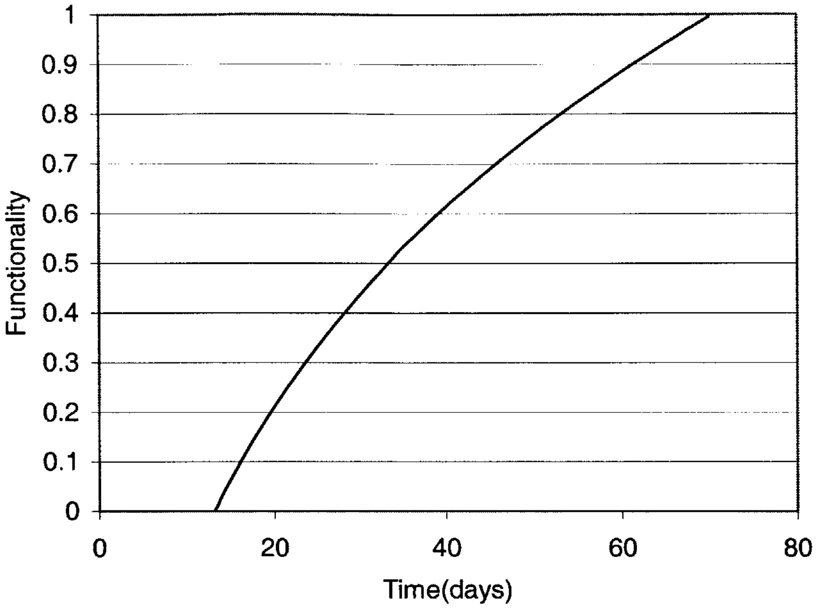

Figure 4-6: A typical functionality restoration curve

function. The curve starts at time=0, with 0 functionality of the element ($c(D) < 0$), and starts to restore at day $t \sim 14$. The element restores complete functionality at $t \sim 70$ days.

From the recovery rate of each element, its total loss in terms of days lost can be obtained from the following equation (Kunnumkal, 2001b):

$$Time\ Element\ Loss\ for\ sector\ i = T_{i,full} - \int_0^{T_{i,full}} F_{i,nointer}(t)d(t) \tag{4.6}$$

where:

$T_{i,full}$: time after the earthquake when sector i restores completely

The equation integrates the functionality of the element i over time until complete functionality is restored, and subtracts it from the days required for it to be completely restored (functional days if there is no damage). The number of total days lost (from Equation 4.6) for each of the structural classification considered is shown in Figure 4-7 (not including the effect of interactions with other sectors).

	a	b	C_0	C_1	C_2
Heavy Industry	0.6	0.25	-0.881	-1.293	0.079
Light Industry	0.6	0.25	-0.881	-1.293	0.079
Food and Drug Industry	0.6	0.25	-0.881	-1.293	0.079
Chemical Industry	0.6	0.25	-0.881	-1.293	0.079
High Technology Industry	1	0.25	-1.793	-2.488	0.066
Commercial	4	0.1	-1.213	-5.433	0.057
Residential	1.3	0.2	-0.707	-2.88	0.173
Lifelines	4.5	0.1	-1.05	-5.562	0.086
Highways	5.5	0.1	-2.416	-6.886	0.05
Major Bridges	1.5	0.15	-1.836	-1.816	0.005
Conventional Bridges	1.7	0.15	-2.013	-1.991	0.005

Table 4.6: Restoration Coefficients

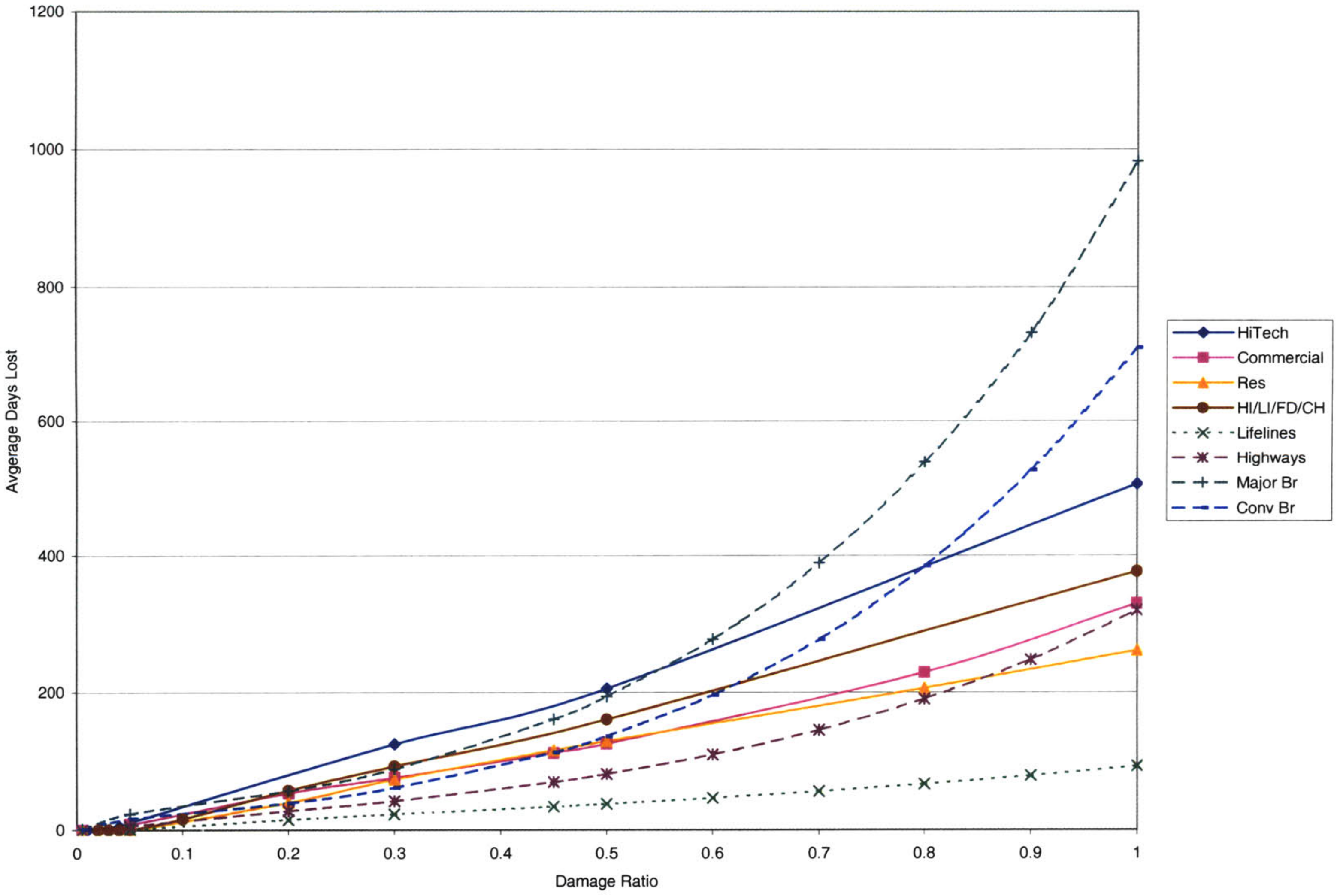

Figure 4-7: Loss in days due to damage

Functionality considering interactions

The final functionality of each element is based on its dependence on the other infrastructure components (see Section 2.3). Also, the recovery of an element itself depends on the functionality of other elements at any time. This methodology addresses this issue through an integrated recovery and interaction model. The main source of the model is Kunnumkal (2001b). The study develops a non-linear multiplicative recovery model, where the effects of reduced functionality of occupancy classes and infrastructure on a class is modeled through reduction factors.

The individual recovery model is now extended to incorporate the effects of interactions. Equations 4.7 and 4.8 summarize the approach used for the modeling of interactions on the node:

$$F_{i,inter}(t) = F_{i,nointer} * \rho_1 \tag{4.7}$$

$$\frac{\partial F_{i,nointer}(t)}{\partial t} = (g_i F_{i,nointer}(t)) * \rho_2 \tag{4.8}$$

$$\rho_1 = \prod_i F_{j,inter}^{\gamma_{ji}}(t) \tag{4.9}$$

$$\rho_2 = \prod_i F_{j,inter}^{\beta_{ji}}(t) \tag{4.10}$$

where:

$F_{i,inter}(t)$: functionality of class i at time t, accounting for interactions with other classes

γ_{ji}: interaction coefficient which gives the effect of functionality of class j on the functionality of class i

$\frac{\partial F_{i,nointer}(t)}{\partial t}$: rate of recovery of class i taking into account the functionality of other components at that time

$g_i(F_{i,nointer}(t))$: the independent rate of recovery of class i

β_{ji}: interaction coefficient that gives the effect of functionality of class j on the recovery rate of class i

Equation 4.7 states that at any time t after the earthquake, the independent

Element	**Lifelines**	**Transportation**
Residential	0.5	0.6
Commercial	0.45	0.85
Heavy Industry	1	0.9
Light Industry	1	1
Food & Drug	0.9	1
Chemical	0.9	1
High Technology	1	1

Table 4.7: Effect of reduced functionality of lifelines and transportation on occupancy classes (γ_{ji})

functionality of a sector ($F_{i,nointer}$) is reduced by a factor ρ_1 to yield the interaction constrainted functionality ($F_{i,inter}$). The factor ρ_1 is equal to a product of the interaction constrained functionalities of all other industries raised by a factor γ_{ji}.

Equation 4.8 states that at any time t after the earthquake, the rate of recovery taking into account interactions ($\frac{\partial F_{i,nointer}(t)}{\partial t}$) is equal to its own rate of recovery ($g_i(F_{i,nointer}(t))$), reduced by a factor of ρ_2. This reduction factor is a product of interaction constrained functionalities of all sectors raised to a factor of β_{ji}.

Table 4.7 lists the factor γ_{ji} for the effect of transportation and lifeline infrastructures on the functionality of various occupancy classes. Using these parameters, the effect of reduced functionality of lifelines and transportation infrastructure on the other node components can be modeled using Equation 4.9. Only the effect of reduced functionality of lifelines and the nodal-transportation component on other occupancy classes have been included till now. The literature lacks information regarding the effect of reduced functionality of residential occupancy class on other classes, and have therefore not been included in this study. The effect of reduced functionality of economic sectors on each other is captured through the input-output model, discussed later in this chapter.

Also, the current literature lacks detailed information on the β_{ji} factor (effect of reduced functionality of other components on the rate of recovery of any component). Therefore, these parameters have not been used in the methodology, and all β_{ji} have been set to a value of 0. The methodology however includes the model to facilitate incorporation of the parameters when they become available.

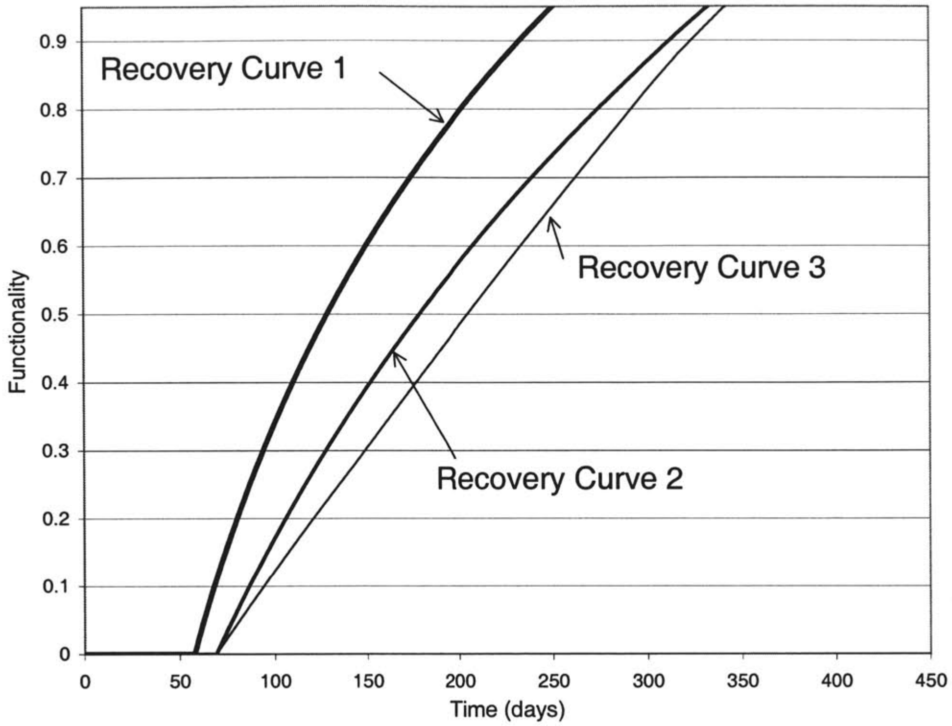

Figure 4-8: Hypothetical recovery curves[7]

Figure 4-8 illustrates three recovery curves. *Recovery Curve 1* shows the recovery independent of all other elements. The curve is obtained from Equation 4.4. *Recovery Curve 2* considers the effects of reduced functionality of other elements on the recovery function. Finally, *Recovery Curve 3* illustrates the recovery curve that considers the reduced recovery rate due to interactions as well as the reduction due to the reduced functionality of other elements.

The total days lost by the sector i due to an earthquake, considering the reduction in functionality due to interactions of sectors can thus be express as (extension of Equation 4.6):

$$Time\ Element\ Loss = T_{i,full,inter} - \int_0^{T_{i,full,inter}} F_{i,inter}(t)d(t) \tag{4.11}$$

where:

$T_{i,full}$: time after earthquake when sector i can function completely considering

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[7] Source: Kunnumkal (2001b)

interactions

$F_{i,inter}(t)$: actual functionality of sector i at time t

We now have the maximum possible functionalities of the sectors on each node that consider interactions among the nodal components. From the known production levels of the economic sectors (pre-earthquake production levels), and knowing the maximum functionality of their corresponding occupancy classes, actual production levels for each sector on the node can be calculated.

However, these production levels do not include the effect of reduced functionality of other economic sectors. The production levels are also controlled by the availability of inputs required for production, demand for the commodity produced by the economic sector, and by constraints in the interregional transportation system. The methodology now applies input-output economic modeling techniques to account for these factors.

4.2.4 Global input-output model

The models developed in Section 4.2.3 predict the performance of industrial sectors based on their pre-earthquake production levels. However, the assumption that all industries always operate at full capacity is incorrect. In a situation where production capacity is destroyed by a catastrophic event like an earthquake, surviving production facilities beyond the affected region may be able to increase their production levels to account for the shortfall. Such productions will however have a higher cost for various reasons including increased costs for operating at a higher then normal production level, overtime to the existing employee force, etc. Thus, industrial production capacity can be relocated (at a cost) and the capacities of the industrial sectors be increased beyond the pre-earthquake production levels. Further, industries also maintain an inventory of its inputs and outputs, and can also obtain inputs through international imports. Thus the effect of reduced functionality in the earthquake affected regions is buffered by such factors.

It is beyond the scope of this thesis to study each of these effects at such a large scale. Therefore a coarse, global (or national) input-output modeling scheme is used to account for the extra slack in the production capacities.

Overview of input-output modeling

Input-Output models provide a framework for the analysis of inter-industry interactions. These models trace the requirements and productions of industrial sectors and consumptions by governments, households, investments and exports. In these models, inputs used in production are related to the output by a fixed coefficient function. These coefficient functions therefore represent the dollar amount of each commodity required to produce a single dollar worth of products. Thus, a framework is developed in which inputs and outputs are related, enabling the study of ripple effects in the economy due to shortages of any of the inputs. These models are extremely data-intensive and range from simple local models to highly complex regional or national models.

In its simplest form, a closed Input-Output framework (having no imports or exports) can be expressed as:

$$Total\ Production = Total\ Interindustry\ Demands + Total\ Final\ Consumptions \tag{4.12}$$

In mathematical terms, for a system of n industries (each producing exactly 1 distinct type of commodity), this can be written as:

$$\mathbf{X} = \mathbf{AX} + \mathbf{c} \tag{4.13}$$

where:

X: a vector of n elements that describes the total production (or output) of economic sectors

A: the input-output coefficient matrix (dimension nxn); element a_{ij} of this matrix is a fixed coefficient that describes the total output (in dollars) of industry i required to produce \$1 of output from industry j; Table 4.8 describes the input-output coefficient matrix used in this methodology

c: a vector of n elements that describes the final demand of each commodity type

AX: a vector of n elements that represents the output of each industry consumed by all other industries to produce their outputs (inter-industry demand)

aij	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0.232	0.000	0.006	0.264	0.003	0.000	0.000	0.000	0.001	0.000	0.010	0.019	0.002
2	0.002	0.166	0.009	0.001	0.028	0.044	0.000	0.000	0.001	0.001	0.102	0.009	0.009
3	0.012	0.017	0.001	0.004	0.008	0.007	0.006	0.006	0.008	0.005	0.007	0.005	0.020
4	0.067	0.000	0.000	0.146	0.006	0.001	0.001	0.001	0.001	0.001	0.003	0.001	0.011
5	0.048	0.013	0.014	0.010	0.224	0.020	0.020	0.005	0.015	0.014	0.068	0.019	0.004
6	0.000	0.011	0.016	0.000	0.002	0.264	0.246	0.087	0.051	0.050	0.002	0.022	0.000
7	0.002	0.006	0.066	0.028	0.009	0.021	0.073	0.042	0.036	0.068	0.003	0.024	0.002
8	0.006	0.022	0.023	0.002	0.005	0.030	0.020	0.132	0.024	0.046	0.005	0.013	0.004
9	0.004	0.002	0.030	0.001	0.001	0.007	0.004	0.081	0.163	0.041	0.001	0.038	0.004
10	0.001	0.001	0.002	0.001	0.000	0.006	0.001	0.003	0.001	0.204	0.001	0.006	0.004
11	0.032	0.017	0.039	0.069	0.072	0.022	0.030	0.031	0.048	0.061	0.212	0.059	0.027
12	0.004	0.004	0.109	0.011	0.006	0.017	0.007	0.009	0.022	0.036	0.015	0.122	0.005
13	0.189	0.237	0.225	0.155	0.209	0.244	0.164	0.157	0.154	0.173	0.183	0.170	0.226

Table 4.8: A Matrix

Equation 4.13 can be easily transformed into:

$$(\mathbf{A} - \mathbf{I})\mathbf{X} + \mathbf{c} = 0 \tag{4.14}$$

where:

I: the identity matrix of dimension nxn

Equation 4.14 signifies that the total production *not* consumed by the industries goes to the final demand component. The final demand can usually be expressed in terms of a particular commodity consumed per person. Thus, for a node having a total population of N, and final demand of a per person for commodity i, c_i can be expressed as $N\text{x}a$.

For a regional analysis, we require an *open* input-output model, wherein there is scope for imports and exports. Thus, taking the possibility of imports and exports into account:

$$(\mathbf{A} - \mathbf{I})\mathbf{X} + \mathbf{c} = \mathbf{P} \tag{4.15}$$

where:

P: vector of n elements, each element equal to the import or export (+ if export, − if import) of that commodity.

For the analysis in this methodology, 13 economic sectors have been considered, each producing exactly 1 type of commodity. Thus, the terms commodity and an industry's output are used interchangeably in the methodology. This classification system for economic sectors has been taken from Okuyama et al. (1999). Table 4.9 describes the 13 commodities used for the analysis.

For the global optimization (balancing the slack in the productions), we assume that the U.S. is a closed system, without any imports or exports. This is a rough approximation, but necessary for simplicity of the analysis.

Assuming that in the pre-earthquake state the production and consumption (final and intermediate) are balanced, the damage to production facilities in the post-

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[8] Source: Okuyama et al. (1999)

Sector	**Description**
1	Agriculture, forestry and fisheries
2	Mining
3	Construction
4	Food and kindred products
5	Chemicals and allied products
6	Primary metals industries
7	Fabricated metal products
8	Industrial machinery and equipment
9	Electronic and electric equipment
10	Transportation equipment
11	Other non-durable manufacturing
12	Other durable manufacturing
13	Commercial, services and government enterprises

Table 4.9: Industrial Classification[8]

earthquake state is bound to create an imbalance. The decrease in production capacities of commodities in the damaged region has been modeled through the fragility and the interaction-recovery model. The production level of each commodity in each node can thus be calculated, ignoring the effect of inter-industry interactions. These are levels of productions assuming that the economy has no flexibility, and none of the economic sectors within or outside the area of influence of the earthquake have the capability of increasing their productions beyond pre-earthquake levels . This is a very strong constraint and not always true in the real world.

We now assume that there is a *slack* of η_i in the production level of industry i on all nodes that accounts for the fact that industries may not normally operate at full capacity. Thus, using the closed form[9] of the input-output equation (Equation 4.14), we can formulate a linear programming (LP) problem that tries to satisfy the final demands. These final demands remain the same in the pre- and post-earthuake scenario. Thus, the optimization tries to increase the production levels to balance the deficit created by the damaged economic sectors in the affected regions. This optimization is performed over the entire U.S. and factors for increase in production levels are applied to industries on all nodes. Again, this is an approximation, and

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[9] Assuming the imports/exports are significantly lesser than the domestic productions/requirements

ignores the spatial distribution of regions or distances when applying the increase in production levels.

The mathematical formulation for the above described LP problem is:

$$\min C_1 \Sigma s_i \tag{4.16}$$

Subject to:

$$(\mathbf{I} - \mathbf{A})[X_{max_i} k_i] - \mathbf{c} + \mathbf{s} = \mathbf{0} \tag{4.17}$$

$$0 \leq k_i \leq \eta_i f_{max} \quad \forall\, i \tag{4.18}$$

where:

A: the A matrix

I: the identity matrix

X_{max_i}: maximum production levels of industrial sector i, aggregated over the entire U.S.

k_i: productivity level of industry i

$[X_{max_i} k_i]$: vector of n elements

c_i: consumption of commodity produced by industry i, aggregated over the entire U.S.

s_i: slack variable for the industrial sector i

η_i: the slack in the industrial production; for example, if $\eta_i = 1.1$, production of commodity i can be increased by 10% over all industrial facilities producing commodity i.

The methodology aggregates all productions and final demands for each economic sector over the U.S. and uses this data in the global input-output model. The global optimization is done by introducing a slack variable, s_i, in the input-output formulation. By minimizing the total slack, or deviation from pre-earthquake state, the model tries to balance the production levels such that the total deviation is minimum. k_i are factors applied to the production level vector ($\mathbf{X_{max}}$) that are bound by reasonable constants η_i (for example, a 10% increase will give a factor of 1.1 in the formulation). The final demands are assumed to be constant in both the pre- and post- earthquake states. Also, the A-matrix remains the same. In an attempt to minimize slack, driven by same pre- and post- earthquake final demands, the production levels of industries across the U.S. are increased until a balance is achieved or a stage where the constraint on any of the k_i's becomes active (i.e., the solution requires that the production levels of some industry be increased by a factor beyond the permissible factor of η_i). In the first case, the factors k_i would be just high enough to make the production of industry i the same in the pre- and post- earthquake state. In the second case (limit on k_i is reached), there will still be some deficits left in the system. Physically interpreting this, an industry will be operating at *full* capacity across the U.S. and will still not be able to balance the deficit created by the damaged industry in the earthquake affected zone, thus creating shortages.

Finally, new production levels adjusted for the shortfall in commodities are obtained. In the next step, the imports and exports from each of the nodes are satisfied using a network optimization algorithm.

4.2.5 Network analysis model

The methodology formulates the inter-nodal transportation network model as a multi-commodity, minimum cost flow (MCMCF) problem. Industrial input-outputs and final demand (consumptions) on the various nodes can be used to derive *exports* or *imports* of commodities. The open form of the input-output model for each node (taking production and final demand variables for that node) as illustrated in Equation 4.19 can thus be used to find the imports and exports from the node.

$$(\mathbf{A} - \mathbf{I})[X_{max_i} k_i] + \mathbf{c} = \mathbf{P} \tag{4.19}$$

where:

P: vector of n elements, each element equal to the import or export (+ if export, - if import) of that commodity.

All variable in the equation, including $\mathbf{A}$, X_{max_i} (maximum production levels, compared to the pre-earthquake levels), k_i (parameter to increase production levels beyond pre-earthquake levels where possible), $\mathbf{c}$ (the consumption levels, fixed in the pre- and post- earthquake state), except $\mathbf{P}$ are known, and can thus be calculated. Knowing the vector $\mathbf{P}$ on each node, the dollar values of these commodities to be imported or exported can be converted to tons of flows, and finally trucks units by using suitable coefficients.

The inter-nodal transportation network formulation minimizes the cost of all commodity flows (in form of trucks) on the network. The following is the mathematical formulation of the optimization:

$$\min \sum_{k} \sum_{(i,j)\in A} c_{ij} x_{ij}^{k} \tag{4.20}$$

Subject to:

$$\sum_{k} x_{i,j}^{k} \leq u_{ij} \quad \forall (i,j) \in A \tag{4.21}$$

$$\mathbf{N}\mathbf{x}^{\mathbf{k}} = \mathbf{P}^{\mathbf{k}}/\lambda^{\mathbf{k}} \quad \forall k = 1,..,n \tag{4.22}$$

where:

c_{ij}: the cost of shipping 1 truck unit on arc (i,j)

x_{ij}^{k}: the flow of commodity k on arc (i,j) in vehicle units

$\sum_k \sum_{i,j} c_{ij} x_{ij}^{k}$: total cost of transportation on the network

u_{ij}: capacity of arc (i,j) in terms of truck units

$\mathbf{P}^{\mathbf{k}}$: vector of exports/imports (indicated by sign) in dollars of commodity k for each node

$\lambda^{\mathbf{k}}$: conversion factor for converting dollar commodity values to vehicle units for commodity k

Equation 4.20 minimizes the total cost of flow, over the entire network, thus optimizing these flows.

Equation 4.21 is the bundle constraint on the network arcs. Each link on the network has a total capacity of u_{ij}, which is used by flows of all commodities k on that link. In physical terms, the overall capacity of a roadway is limited by the maximum number of vehicles. The total flow of commodities that can flow on a link (in form of trucks) is therefore limited by the overall capacity constraint.

Equation 4.22 is the flow balance constraint on each node. The node-arc incident matrix[10] N times the flow of commodity k on each arc (x^k) gives the total outflow or inflow of that commodity on each node, and is equal to the export or import (P^k/λ^k) of commodities in vehicle units on that node.

The algorithm tries to balance the imports and exports from all nodes on the transportation network by minimizing the total cost while respecting the capacity constaints.

4.2.6 Local (nodal) input-output model

The methodology carries out a "local" or nodal input-output analysis. The import/export requirements from the node may not be fulfilled because of transportation network constraints (e.g., the transportation links around the node are non-functional or at capacity), or due to the overall deficit of a commodity over the entire U.S. In either case, some nodes will not be able to import/export from/to other nodes. Therefore, the node will have to try and achieve a balance with the maximum possible imports or exports that can supplied by the network model. This may require lowering production levels to accommodate the shortage (when it is intermediate inputs to industries), or reduction in levels of final demand.

Physically interpreting this through an example, a node may require 100 units of product A as inputs to industries and as final demands for the population, but due to shortages or network constraints, this requirement cannot be satisfied and the network dictates that the node can only receive 50 units of that commodity.

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[10] The node-arc incident matrix stores the network as an nxm matrix that contains one row for each node of the network and one column for each arc. Each element of matrix is either 1 or -1, indicating that the arc (column), either comes out, or goes into the node (row). Refer Ahuja et al. (1993) for further details

Therefore, the node will have to adjust the production levels of its industries to "make-do" with the available import levels, and/or the general population will have to curb their consumptions of the commodity. This requires an input-output analysis, as the production levels and final demands of all industries are connected through input-output interactions. For example, lowering production level of an industry A on a node due to shortages in one of its requirements, B, will also reduce requirements of other commodities needed by industry A, as well as create deficits of A itself. A "balancing" of all production levels is thus required to be consistent with the available imports/exports.

For this purpose, the input-output model is applied on each node again. The input-output problem is formulated as a linear program and optimized for the given network balances.

On each node:

$$\max -C_1 \sum_i s_i + C_2 \sum_i f_i + C_3 \sum_i c_i \tag{4.23}$$

Subject to:

$$(\mathbf{I} - \mathbf{A})[X_{max_i} k_i f_i] - \mathbf{c} \pm \mathbf{s} = \pm \mathbf{P} \tag{4.24}$$

$$0 \leq f_i \leq f_{max} \quad \forall\, i \tag{4.25}$$

$$0 \leq c_i \leq c_{max} \quad \forall\, i \tag{4.26}$$

where:

$\mathbf{A}$: the A matrix

$\mathbf{I}$: the identity matrix

X_{max_i}: maximum production levels of industrial sector i

f_i: functionality level of industry i

k_i: factor that increase production to account for deficits (from global input-output optimization)

c_i: final demands of commodity produced by industry i

P_i: import/export levels of commodity produced by industry i (from the network algorithm, Equation 4.2.5)

s_i: slack variable for the industrial sector i

C_1, C_2, C_3: variables that describe the importance of balancing the imports/exports to the network-model values, producing commodities, and maintaining consumptions in final demands, respectively

Through this optimization process, each node in the network tries to minimize deviation from the network import/exports (by minimizing the sum of s_i) and also tries to maximize production levels, as well as final demands (by maximizing the sum of f_i and c_i).

The constraint 4.24 is the open form of input-output system of equations. It related the imports/exports, final demands, production levels, and the slack variable. The slack variable is signed in the constraint and the sign depends on the polarity of P_i. For a particular commodity on a node, it is assumed that the imports/exports derived from the network are hard constraints. Thus, equalizing the polarity of s_i and P_i guarantees that the export/import from the node is smaller, or at best equal to the network values. This is also necessary for reasonable convergence of the network/node-balancing iteration scheme.

Constraint 4.25 implies that the production levels are constrained by the maximum damaged functionalities of the economic sectors. The factor f_{max} goes to 1 if the industrial sector is undamaged. Similarly constraint 4.26 limits the consumption levels to the pre-earthquake scenario. Changes in final demand due to factors other than shortages are not considered in the methodology [11], and therefore the maximum consumption levels are assumed constant for any node.

The coefficients C_1, C_2, and C_3 are used as factors for s_i, f_i, and c_i in the objective function respectively. By varying these coefficients, weights can be attached to the importance of balancing the actual imports/exports to the network supplied

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[11] For example, increase in cost of commodities, or lowering of personal savings

import/exports, importance of keeping production levels to the maximum, or keeping the final demands satisfied. These coefficients can also be policy variables, dictating the share of the total deficit borne by the population and the industries (as each commodity is used by industries as inputs as well as by the general public). It can be observed that giving higher weights to the final demands, the industrial productions suffer and are lowered (due to the shortages in inputs), causing a ripple effect where the productivity of the entire economy goes down, creating further shortages. Therefore, it is necessary for the industries to be operational, while importance should also be given to final demands.

The LP formulation finally outputs the production levels as well as the consumption levels that best utilize the available imports and exports. If the import/export levels after this balancing are same as the import/exports as dictated by the network, the node is assumed to be balanced. However, if the node is not able to balance itself, the closest possible import/exports are found through the LP formulation. The values of productions and final consumptions that best balance the input variables are obtained from the node-balancing LP formulation, and they are used to calculate new, feasible imports and exports. These import/exports are then again supplied to the network flow model to be balanced. Thus, an iteration of the network flow model is performed, and the import/export values obtained for each node are supplied back to the nodal input-output model. This process is repeated until the node (and all other nodes on the network) are found to be feasible.

Finally, the whole process is repeated in time. The interaction-restoration model develops new system states at each time step, and the entire process starting from the global input-output balancing is repeated. A balance is achieved at each time step and the system comes closer to pre-earthquake system state as the model progresses in time. The process is thus repeated until complete functionality of all elements is restored or the loss of function is negligible.

The direct economic loss immediately after the earthquake, as well as the indirect economic loss at each time-step can also be calculated. The direct economic loss due to failure of structures are calculated using Equation 4.2, which says that damage factor is the ratio of *repair cost* to the *replacement cost* of the structure. Knowing the damage factor (from fragility curves) and the replacement cost of all building stock, lifelines, and transportation infrastructure, direct economic loss can be calculated. The indirect economic loss is calculated through the evaluation of distortions in the economic framework. The reduction in production levels of industries in the damaged region are an obvious form of economic loss, and can be evaluated at each time-step by calculating the production levels of industries on all nodes and comparing them with levels in the pre-earthquake state. However, evaluation of other economic effects such as losses/gains due to increases in production levels elsewhere to account for reduced levels in the directly influenced areas requires more work. Further, several other parameters such as government funding levels, insurance, economic effects of rebuilding efforts, etc. also need to be considered while calculating the total loss. Further work has to be done towards developing an economic model that can address these issues.

The next chapter presents and discusses the results of a New Madrid earthquake scenario, together with details of the implementation and data requirements.

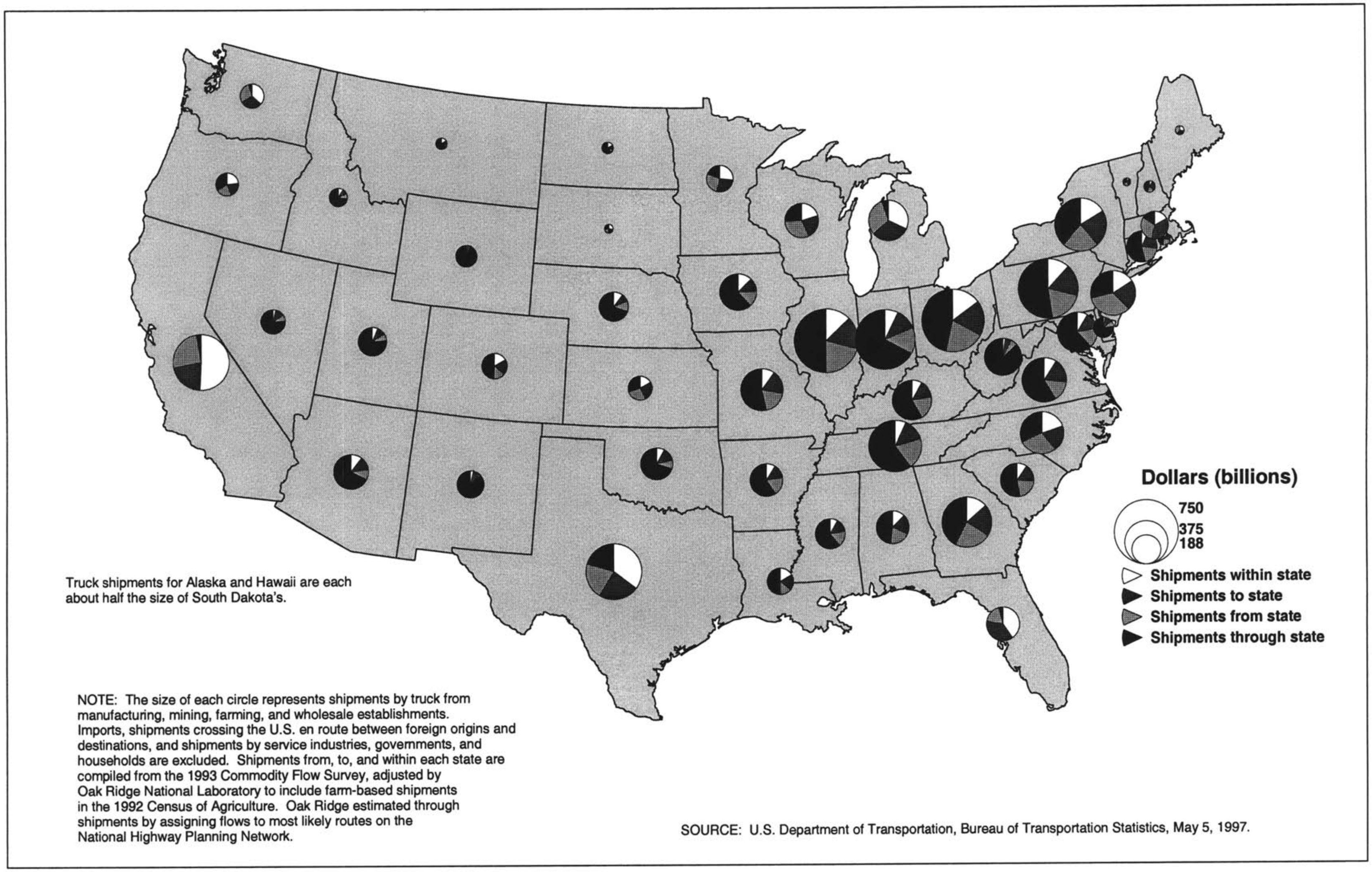
Chapter 5

New Madrid Earthquake Scenario

5.1 The New Madrid Scenario Earthquake

The New Madrid Seismic Zone lies within the central Mississippi Valley, extending from northeast Arkansas, through southeast Missouri, western Tennessee, western Kentucky to southern Illinois. The New Madrid Seismic Zone is so named because a small town of New Madrid was the closest settlement to the epicenters of the great 1811−1812 earthquakes. These earthquakes had dramatic effects on both land and the Mississippi river (Johnston and Schweig, 1996). There is contention among geologists about the exact magnitude of the earthquakes, but the most widely cited estimates are of **M 8**. There is evidence that a repeat event of the 1811 – 1812 earthquakes in the New Madrid Seismic Zone is highly probable. A typical recurrence interval of $\sim$ 500 years is predicted for the "characteristic" earthquake of intensity **M** $\sim$ **7.5** or higher (Atkinson et al., 2000); however, a repeat of the 1811-1812 earthquake or earthquakes of lesser intensities are possible even within a shorter time-span.

It is widely recognized that a repeat of such a large earthquake in this region could have devastating consequences on the regional Midwestern economy, with repercussions at the national level (Central U.S. Earthquake Consortium, 2000). The Midwest region of the U.S. is placed strategically in the central part of the continent, and is an economically active region, acting as a consumer and a source to many industries elsewhere. Figure 5-1 shows the high value of commodity flows that are shipped from, shipped to, or pass through the Midwest region, emphasizing the strategic importance of this region. Damage to production capabilities of this region can thus cause ripple effects throughout the regional as well as the national economy and even international economy. Also, damage and consequent constraints in the transportation network of this region may cause widespread losses as the highway network is used extensively to transport these commodities.



Truck shipments for Alaska and Hawaii are each about half the size of South Dakota's.

NOTE: The size of each circle represents shipments by truck from manufacturing, mining, farming, and wholesale establishments. Imports, shipments crossing the U.S. en route between foreign origins and destinations, and shipments by service industries, governments, and households are excluded. Shipments from, to, and within each state are compiled from the 1993 Commodity Flow Survey, adjusted by Oak Ridge National Laboratory to include farm-based shipments in the 1992 Census of Agriculture. Oak Ridge estimated through shipments by assigning flows to most likely routes on the National Highway Planning Network.

SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, May 5, 1997.

Figure 5-1: Value of truck shipments by state

This chapter describes a scenario analysis of a major New Madrid earthquake, and applies the methodology developed (described in Chapter 4) to study its effects and economic losses. The results are preliminary, and require considerable refinement and additional development to be used as a decision support tool for loss mitigation. The scenario results *do* however provide a "proof of concept" of the methodology, and an example where basic effects of the earthquake can be understood.

The following section of this chapter describes the data requirements and implementation of various models. The last section presents and discusses the results from the scenario analysis.

5.2 Data Requirements

The national level geographical setup of the model includes nodes, where all infrastructure and economic activity are aggregated, and highway links between these nodes. Consistent with the macroscopic scope of the methodology, significant aggregation has been done (see Section 2.2). As can be clearly observed from Figures 4-1 and 4-2, the metropolitan areas and counties with high population densities are concentrated close to the intersections of the National Interstate Highway System, or where the network is dense. Thus, it is a reasonable assumption to consider these intersections as nodes for the purpose of our analysis. A county was found to be a good geographical entity to be aggregated and associated with each node. The data availability for counties is consistent with the requirements of this methodology. Each county in the contiguous U.S.[1] is thus associated with a node. However, there are several regions that have a very high density of highways and highway intersections. These areas thus have a high density of nodes and using all of these nodes for aggregating counties would yield a non-uniform distribution of regions. Several nodes in the high density regions were thus ignored while aggregating counties, and treated as virtual nodes (having no counties associated with them) to retain the network

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[1] Alaska and islands were ignored, because they are not connected by the National Highway System. Further, they have negligible import/export associated with them, and can be ignored for the macroscopic analysis

topology of the highway system.

As described in Section 2.2, the geographical region within the direct influence of the earthquake can be modeled in greater detail for better accuracy and to better account for local effects. The density of these nodes is thus higher in the Midwest regions (fewer intersections ignored for the purpose of aggregation) and much lower over the rest of the U.S. Finally, counties are associated with these nodes by finding the node closest to the centroid of each county. Figure 5-6 shows the regions aggregated by the above mentioned procedure.

The highway sections between these nodes are considered as single entities (ignoring the "shape", temporary changes in the number of lanes, etc.). Each highway section in the Midwest region (radius of approximately 100 miles from the epicenter) has several bridges associated with it. Similar to the nodes, the transportation network in the Midwest region has been modeled with greater detail. Thus, all primary roads (including State Highways and U.S. Highways) have been added to the region; the Interstate highway network was used for the rest of the U.S.

The next two sections describe the data collected for the nodes and links to be used in the scenario analysis.

5.2.1 Node data

The node parameters include data regarding the physical built-up areas for different occupancy classes, population, and production levels of economic sectors. All of this data is collected or calculated for each county in the U.S. and aggregated to form nodes. The following sections describe the physical and economic data aggregated on nodes.

Physical infrastructure

HAZUS (National Institute of Building Sciences, 2000a) was used as the main source of data regarding building stock content. HAZUS includes data regarding floor areas of each type of occupancy class in every county. The occupancy classes included for

Occupancy Class	**Label**
Single Family Dwelling	RES1
Mobile Home	RES2
Multi Family Dwelling	RES3
Temporary Lodging	RES4
Institutional Dormitory	RES5
Nursing Home	RES6
Retail Trade	COM1
Wholesale Trade	COM2
Personal and Repair Services	COM3
Professional/Technical	COM4
Banks	COM5
Hospital	COM6
Medical Office/Clinic	COM7
Entertainment & Recreation	COM8
Theaters	COM9
Parking	COM10
Heavy Industry	IND1
Light Industry	IND2
Food/Drugs/Chemical	IND3
Metals/Minerals Processing	IND4
High Technology	IND5
Construction	IND6

Table 5.1: HAZUS classification of occupancy classes

analysis are described in 5.1. These occupancy classes were mapped onto the occupancy classification used in this methodology. The mapping is defined in Table 5.2. For example, all classes of residential buildings in HAZUS were aggregated to form the residential (RES) occupancy class for the scenario.

ArcView GIS[2] was used for aggregating data and the GIS analysis. For example, analysis involving aggregation of counties using shortest distance analysis[3] and associating bridges with the highways was done using the system.

ESRI's 1999 Data & Maps Data Sets were used for the GIS database including the state, county and national boundary. The data was used for finding centroids of

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[2] A popular desktop Geographical Information System developed by Environment Systems Research Institute (ESRI)

[3] After a distribution of "real" nodes has been defined on the network, each county looks for the node closest to it (from the centroid of the county) and associated with it for aggregation

Occupancy Classes in Model	**HAZUS Occupancy Classes**
Residential	RES1, RES3, RES4, RES5
Commercial	COM1, COM2, COM3, COM4, COM5
Heavy Industry	IND1, IND4
Light Industry	IND2
Chemical	IND3
Food & Drug	IND3
High-Technology	IND5

Table 5.2: Mapping of HAZUS occupancy classification to the classification in the methodology developed

the counties, and visualization of results.

Economic data

Bureau of Transportation Statistics' (BTS) 1997 Commodity Flow Survey (CFS) (Bureau of Transportation Statistics, 1999) data and HAZUS' economic data (National Institute of Building Sciences, 2000a) were used in the analysis as indicators of commodity productions in counties across the U.S. The CFS data gives shipments of commodities originating from a state and shipped to other states or to destinations within the state. The data is ideally suited for a commodity flow analysis (as it was developed for recording commodity flows, and thus a suitable classification). However, this data is insufficient in defining the entire economic activity of a region. For example, it does not detail activity in the "construction" or the "services" sectors. HAZUS was used to augment the CFS data in such cases. The HAZUS economic classification was not suitable for the transportation system analysis, as it aggregated industries that do not have homogeneous commodity flow equivalents. For example, manufacturing industries, that can produce commodities of varying physical characteristics are grouped into 1 sector. This is not acceptable for the purpose of transportation system analysis, as it is difficult to calculate suitable commodity/vehicle equivalents for such groups. Also, such a grouping reduces the flow of commodities on the inter-nodal network. As different types of commodities produced by a single sector are "equivalent", a substitute for a commodity might be available locally. For example, electronic equipments might be manufactured in California, and are needed by industries in the Midwest; however, as all manufacturing is grouped into one sector, the model may consider apparel produced in the Midwest as a substitute for electronic equipment. Thus, the more detailed CFS-based classification was used instead of the HAZUS classification to reduce this effect in the model.

The CFS database includes data originating from states. Thus the data had to be disaggregated by population for all counties in the U.S. The HAZUS database directly describes production levels for economic sectors for the counties, therefore no disaggregation was required. Finally, data for the counties were aggregated to produce data for the nodes.

Table 5.3 details the 13 economic sectors used in this methodology, description of the sector, source of data, fragility classification used for earthquake vulnerability (by occupancy class), and the two-digit SIC code[4]. The system of economic sector classification used in the methodology and data collection methods are preliminary, and further work will attempt to add accuracy and detail.

The node also includes population data. This data is used in data preparation including disaggregation of data (CFS data is defined for states), and calculating final demand levels (final demands are calculated as the product of population on the node and consumption/person). Figure 4-2 shows the population density of counties. Population attributes for counties are obtained from the 1990 U.S. Census of Population and Housing.

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[4] The Standard Industrial Classification (SIC) codes were developed by the United States government in the 1930s and are popularly used to classify businesses according to their primary type of activity.

Sectors	Title	Source	Fragility Classification Code	SIC (2-digit)
1	Agriculture, Forestry and Fisheries	HAZUS	-none-	01,02,07,08,09
2	Mining	CFS	-none-	10, 12, 13, 14
3	Construction	HAZUS	-none-	15, 16, 17
4	Food and Kindred Products	CFS	F&D	20
5	Chemicals and Allied Products	CFS	Chem	28
6	Primary Metals Industries	CFS	HI	33
7	Fabricated Metal Products	CFS	HI	34
8	Industrial Machinery and Equipment	CFS	HI	35
9	Electronic and other Electric Equipment	CFS	HiTech	36
10	Transportation Equipment	CFS	HI	37
11	Other Non-durable Manufacturing	CFS	LI	21-23,26,27,29-31
12	Other Durable Manufacturing	CFS	LI	24,25,32,38,39
13	Service and Government Enterprises	HAZUS	COM	40-42,44-65, 67 70,72,73,75,76

Table 5.3: Mapping of economic sectors used in the methodology to the occupancy classes and SIC codes

5.2.2 Link data

The National Transportation Atlas Database (NTAD) 2000 (Bureau of Transportation Statistics, 2000) was used to obtain a GIS system of the Interstate Highway Network. The NTAD database is detailed in representing the highway system and includes several primary and secondary roads. However, for the methodology developed in this thesis, a lower level of detail was required. Thus, the Interstate Highways were extracted from the database through the GIS system. A certain amount of detail was preserved in the Midwest region for accuracy in the area of direct influence. Figure 5-2 shows the road network used for the scenario.

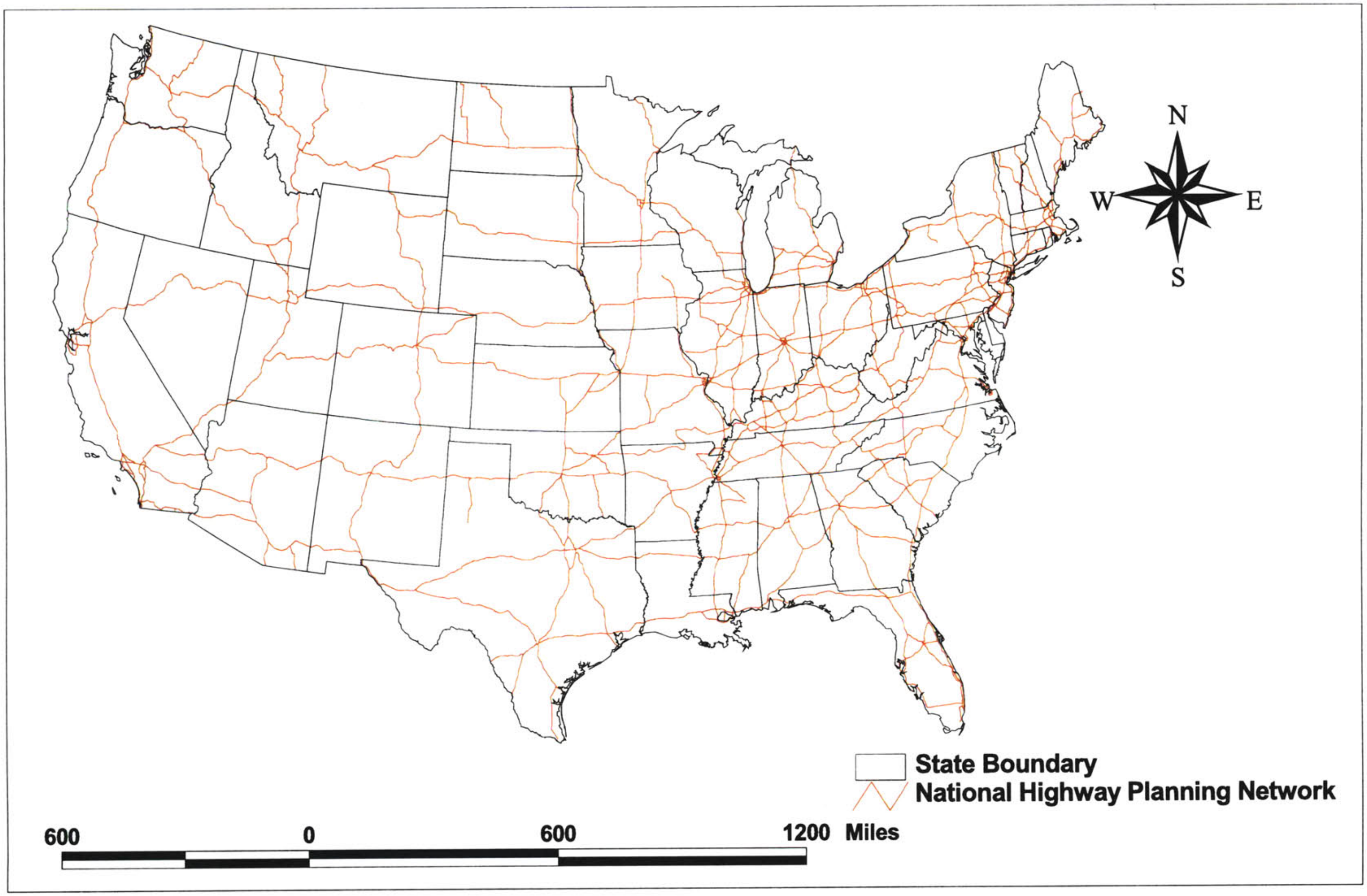

Figure 5-2: Highway network used in the scenario analysis (Source: National Transportation Atlas Database 2000, Bureau of Transportation Statistics)

The links in the analysis are formed of sections of highways between nodes. These links are uni-directional, and each highway section is defined by two links in the opposite direction. The sections and these links are assumed to have a capacity defined by the most constrained section on the link. For example, a 2 lane Interstate (each direction) may have small highway sections that have larger number of lanes; however, for the analysis the whole link was assumed to have 2 lanes. The length of each link is used as a measure of the cost of traversing that link. This is a simplifying assumption and ignores the fact that the transportation cost also depends on congestion and time of travel.

The Federal Highway Administration (FHWA) maintains the National Bridge Inventory (NBI) system. The NBI is an extensive database of highway bridges in the U.S. Each bridge has detailed data regarding geographical coordinate, structural characteristics, traffic characteristics, number of lanes, etc. This bridge inventory database system was used in the methodology for modeling bridge damage and ultimately, link capacity. The database required extensive processing and simplification before it could be integrated into the GIS system consisting of the highway network system (NTAD). Only bridges within a rough radius of 100 miles from the New Madrid Seismic Zone were extracted from the database. These bridges were further classified according to the highways they were on. Only bridges on highways modeled in the scenario were then extracted from this set of bridges. Finally, more than 2000 bridges were obtained that had to be associated with the highways system. A "closest feature algorithm" in the GIS system was then used to associate each bridge to the links in the highway system. This was necessary as the functionality of a link is dictated by the functionality of the bridges on it, and this analysis would not be possible without the knowledge of bridge association with highways. Figure 5-3 shows the bridges in the Midwest region overlayed onto the highway database.

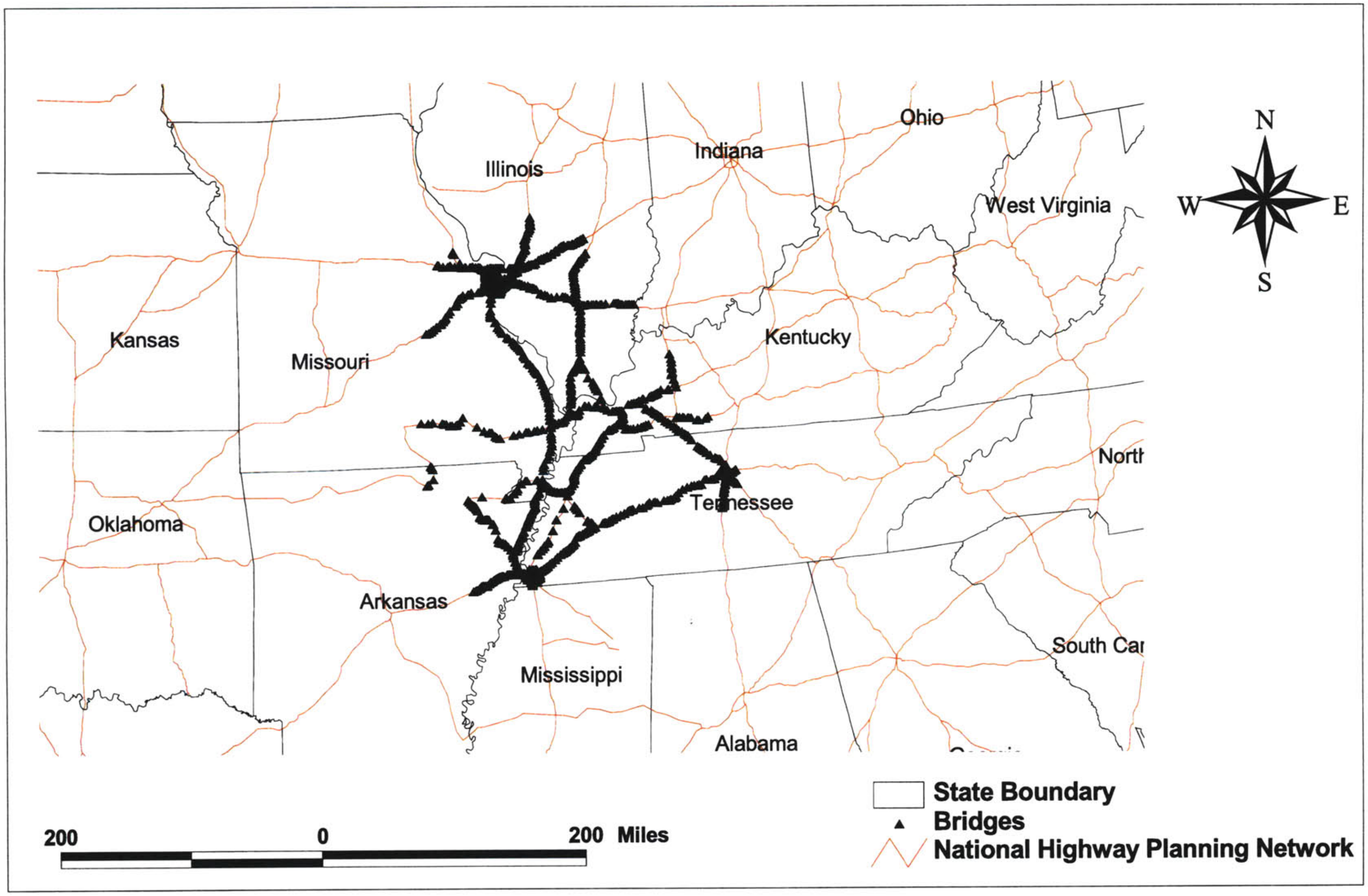

Figure 5-3: Highway bridges used in the scenario analysis (Source: National Bridge Inventory Database, Federal Highway Authority

Figure 5-4 summarizes the databases incorporated in the methodology. Data regarding population, county boundary information, transportation network configuration, and bridges are integrated into the GIS database. This GIS database was converted to a text-based database. For example, the network topology was stored as a series of node-to-node pairs. Similarly, node information was converted to a tabular form, each node carrying details such as geographical coordinates, population, etc. Other node data including build-up areas and production levels (sector-wise) were aggregated separately and associated with the text-based node data abstracted from the GIS.

The road network used in the scenario earthquake includes the interstate highway network, with greater detail in the Midwest region. Approximately one-third of these intersections were used to aggregate counties and the rest were only considered for retaining the network configuration (See Figure 5-5). The final network had 152 "real" nodes, 410 highway intersection nodes, and 1440 links (720 distinct highway sections, each represented as a link in either direction).

The final system of abstracted nodes and links used in the scenario analysis is illustrated in Figure 5-5, and the aggregated regions are shown in Figure 5-6.

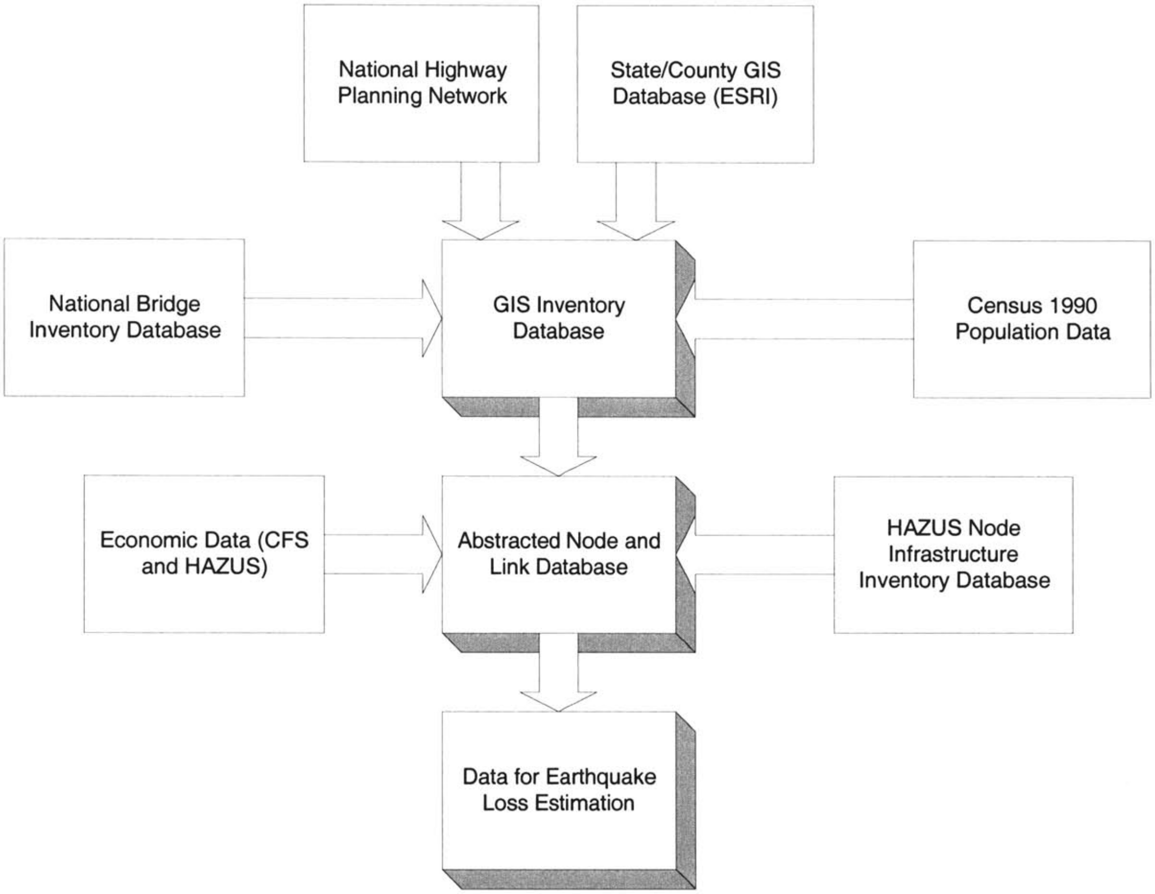

Figure 5-4: Data preparation for the scenario

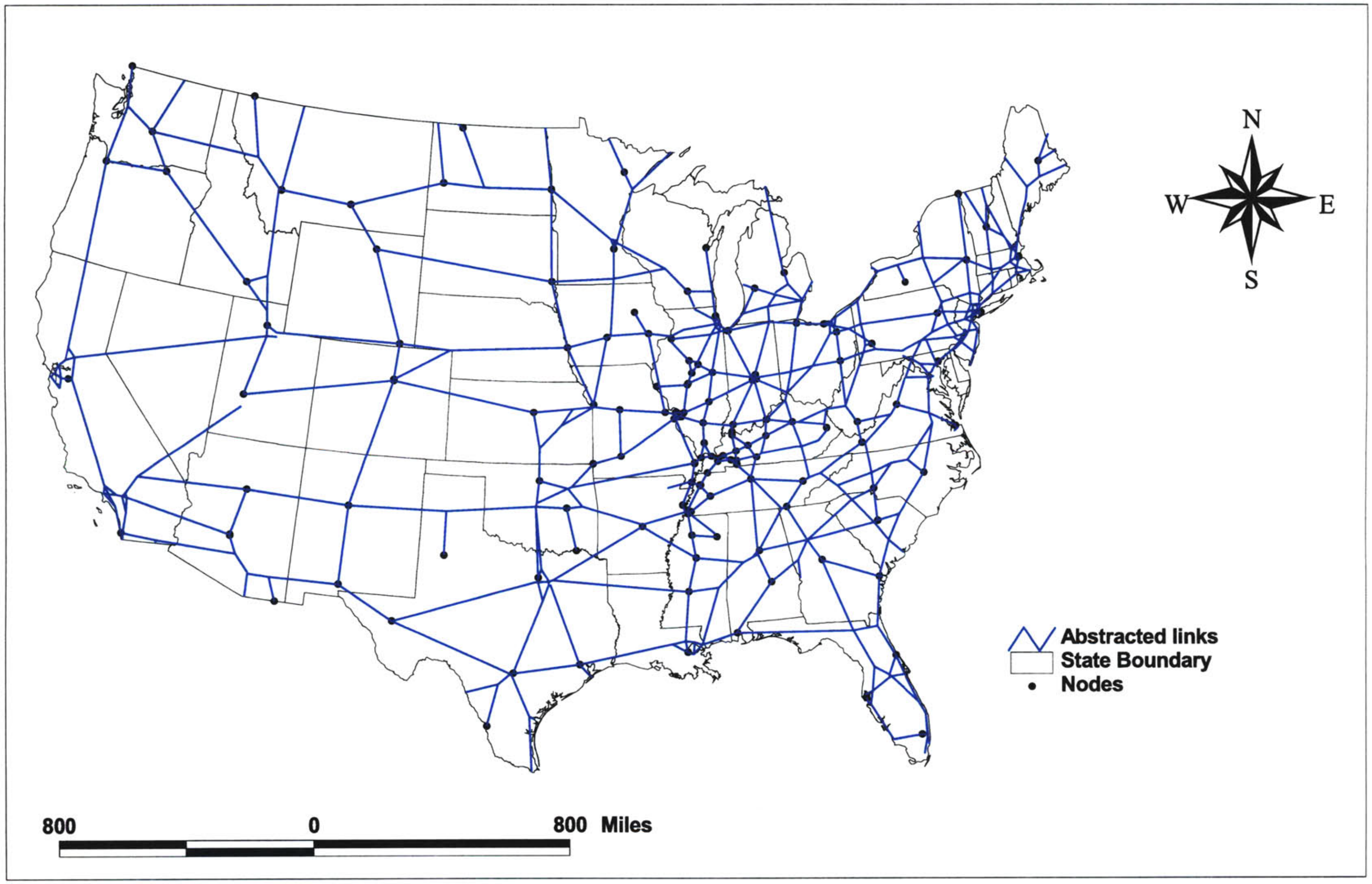

Figure 5-5: Abstracted links and nodes used in the scenario

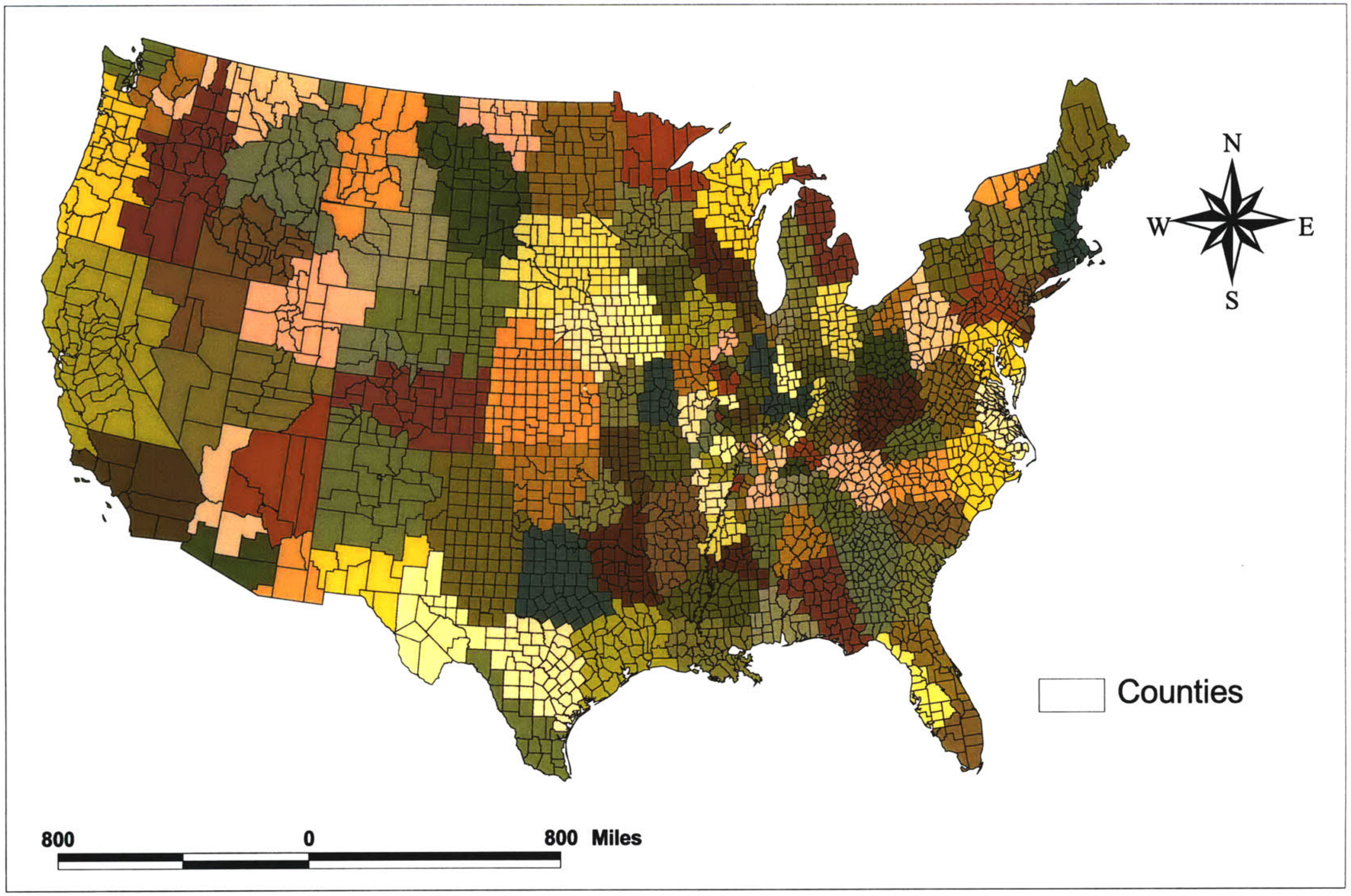

Figure 5-6: Counties aggregated into regions (solid colors indicate aggregated regions)

5.3 Implementation of the Methodology

The model was implemented in the C++ programing environment. The flow of the computer program is illustrated in Figure 5-7. Implementations of LP and MCMCF solvers available in the public domain were integrated with the C++ code developed. LP_Solve[5] was used for solving LP problems in the methodology and the Interior Point Method (IPM)[6] based IPM multi-commodity flow problem solver(Castro, 2000) was used for solving the MCMCF problem from within the implementation of the methodology. The code operates in an integrated, sequential manner, and does not require human intervention after the initial model setup.

Typical run-times for the entire methodology on a standard current desktop is 1 hour for all iterations until complete system functionality is restored. This runtime is however dependent on several factors, including:

1. Size of the discrete time steps considered for restoration

   The analysis divides the time after the earthquake until recovery into several time steps. It is assumed that a time interval has a constant system state. Therefore, the run time increases linearly with the number of time steps. Considering bigger time steps may however lose accuracy. The recovery immediately after the earthquake is quick, and taking larger time steps may forgo accuracy as the assumption of constant functionality over this time period may not be within reasonable limits of accuracy. However, the system components recover gradually after a certain amount of time, and taking broader time intervals then can dramatically increase the efficiency of the program. Therefore, the time intervals considered in the analysis are variable, with smaller time steps immediately after the earthquake, and greater time steps as the system recovers its functionality.

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[5] LP_Solve is non-commercial linear programming code written in ANSI C by Michel Berkelaar, who claims to have solved problems as large as 30,000 variables and 50,000 constraints. Available at: ftp://ftp.es.ele.tue.nl/pub/lp_solve

[6] An advanced algorithm for finding solutions to constrained optimization problems. Discussion of the algorithm is beyond the scope of this thesis.

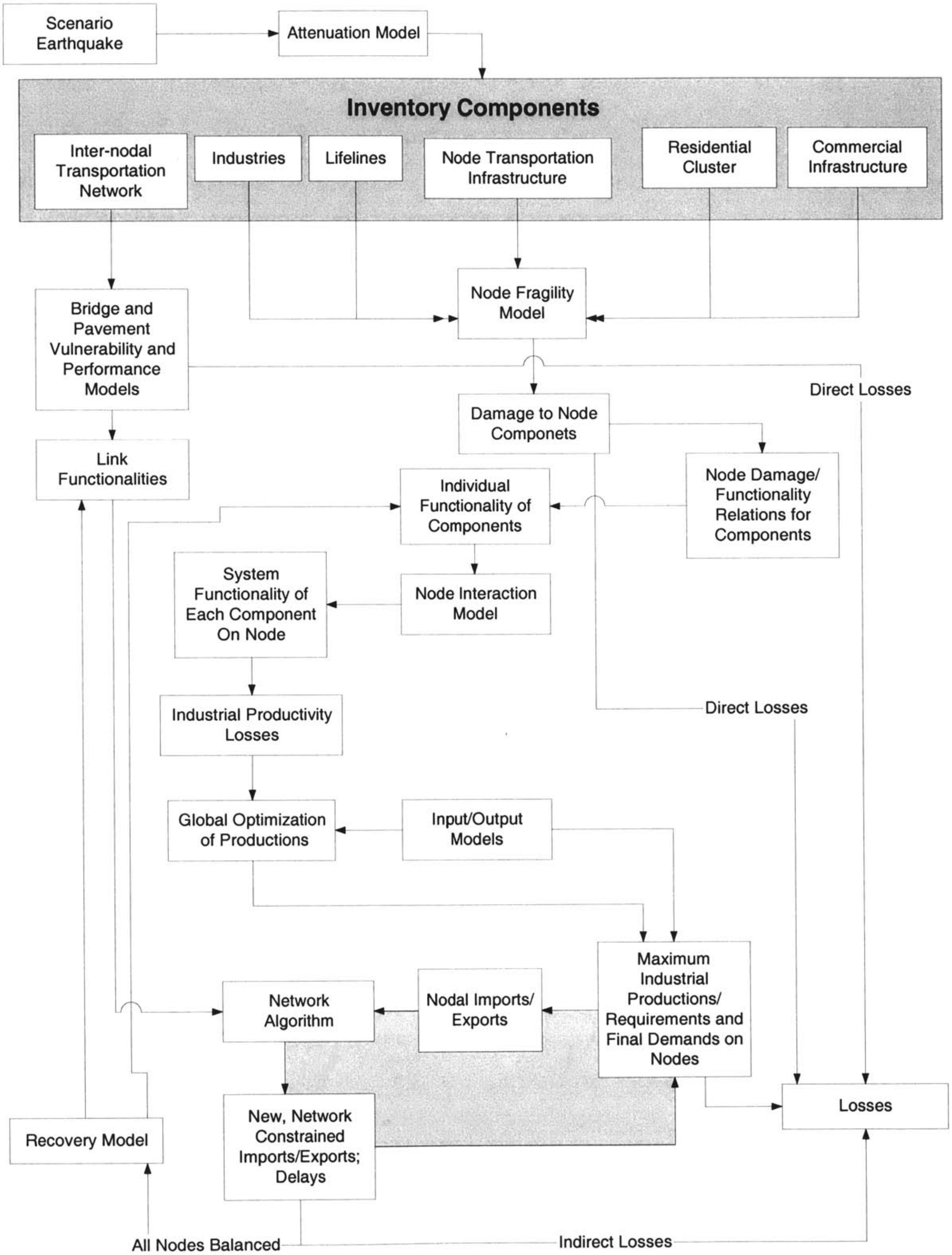

Figure 5-7: Summary of the methodology

2. Size of the network

   Considering more nodes and links (i.e., disaggregating the U.S. into smaller regions for the analysis, or considering a denser highway network) increases the runtime in almost all methodology elements. The modules of the implementation that require a high runtime include the MCMCF solver (IPM) and the node balancing LP solver (LP_sover). Both of these elements are sensitive to the size of the network. The runtime of the LP sover is linear in the increase of the number of nodes (as it is executed exactly once for each node in every iteration). However, the MCMCF solver has a much higher sensitivity, and becomes very expensive to solve for networks bigger than 1000 nodes.

3. Intensity of the earthquake

   A higher earthquake intensity causes higher levels of damages, and thus more imbalance in the network. Therefore, generally speaking, more iterations will be required to remove infeasibilities at each time step. The time to recover the entire system also increases because of the higher initial damage. Thus, more time steps have to be considered, increasing the total runtime.

4. Tolerances in the network

   The accuracy desired can change the runtime of the algorithm. For example, a smaller tolerance while comparing the network output solution and node balances from the local input-output model might result in declaring the node infeasible and need another iteration.

5. Capacity constraints in the network

   The network solver is sensitive to the capacity constraint in the network. Tighter capacity constraints in the network causes links to reach capacity, and hence alternative solutions have to be sought. Refer Castro (2000) for further details regarding sensitivity of the MCMCF solver to various parameters.

6. Other implementation issues

Implementation issues include the method of calling the external modules (LP_solver and IPM), data handling, and data structures used in the implementation. Changing parameters of the implementation may lead to greater efficiency.

The next section discusses the results from a scenario earthquake of intensity **MMI = 11** in the New Madrid Seismic Zone.

5.4 Results of the Scenario Earthquake

Figure 5-8 illustrates the ground shaking intensities at various points in the Midwest region. The simple Bollinger function (see Section 4.2.1) used in the analysis does not consider the geological conditions, therefore the ground shaking intensities are only a function of the distance from the epicenter. The intensities are perfectly concentric with reference to the epicenter. In reality however, the intensities vary greatly with local site conditions and other geologic features of the region. Geologists have suggested that the actual shape of the intensity contours of an earthquake will be elongated along the Mississippi river Toro and Silva (2001).

Figure 5-9 shows the damage to the Food and Kindered Products Industry. The damage across each region considered is constant, and is defined by the distance of the centroid of the region from the epicenter. Damage beyond a certain distance when the intensities fall below MMI$\sim$ 6 do not produce any damage. These damages are calculated for each economic sector with a vulnerable occupancy class associated with it (see Table 5.3 for exact mapping), residential, node transportation, lifelines, and interregional highways and bridges.

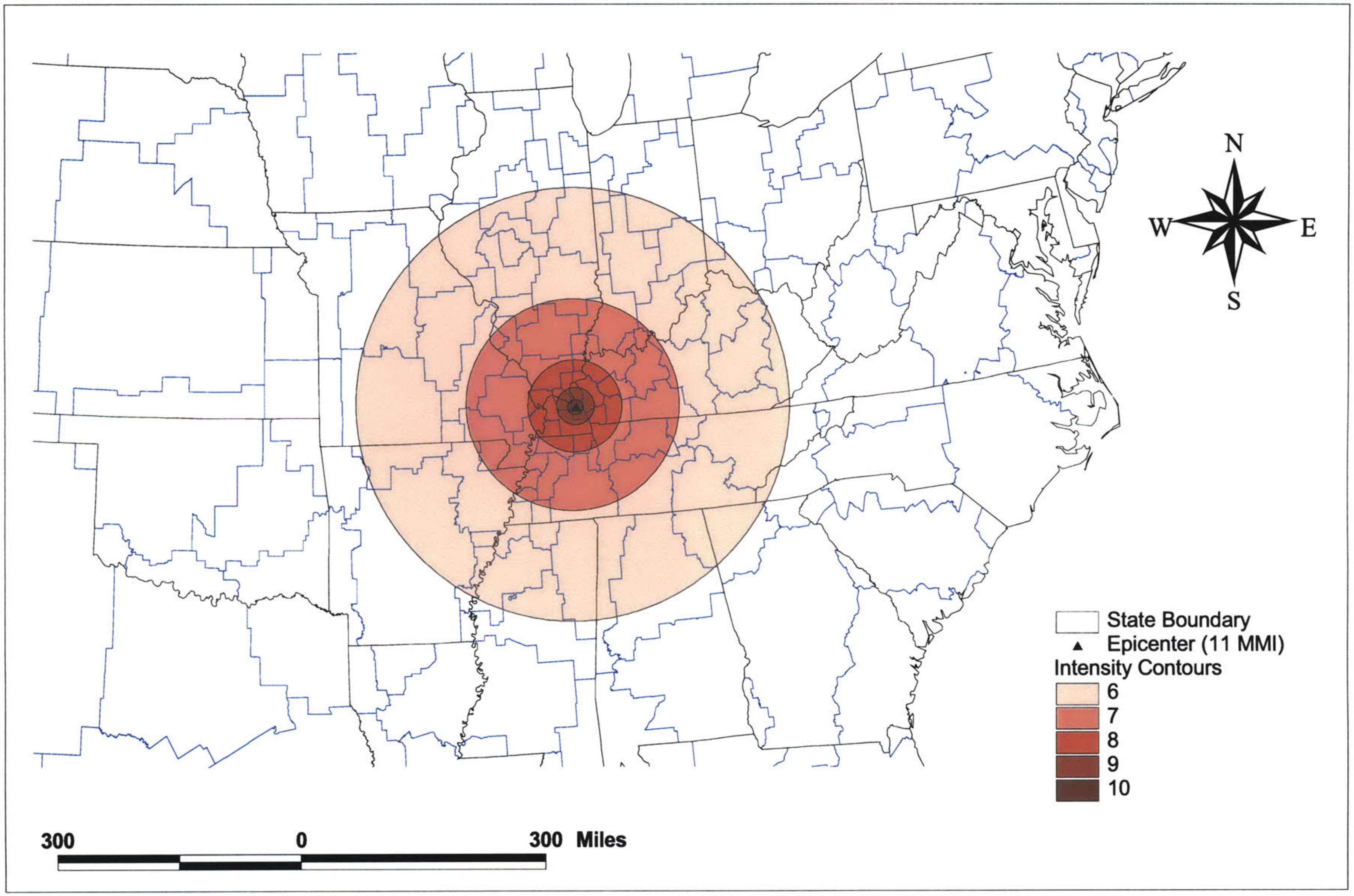

Figure 5-8: Propagation of ground shaking intensity on the MMI scale for the scenario earthquake

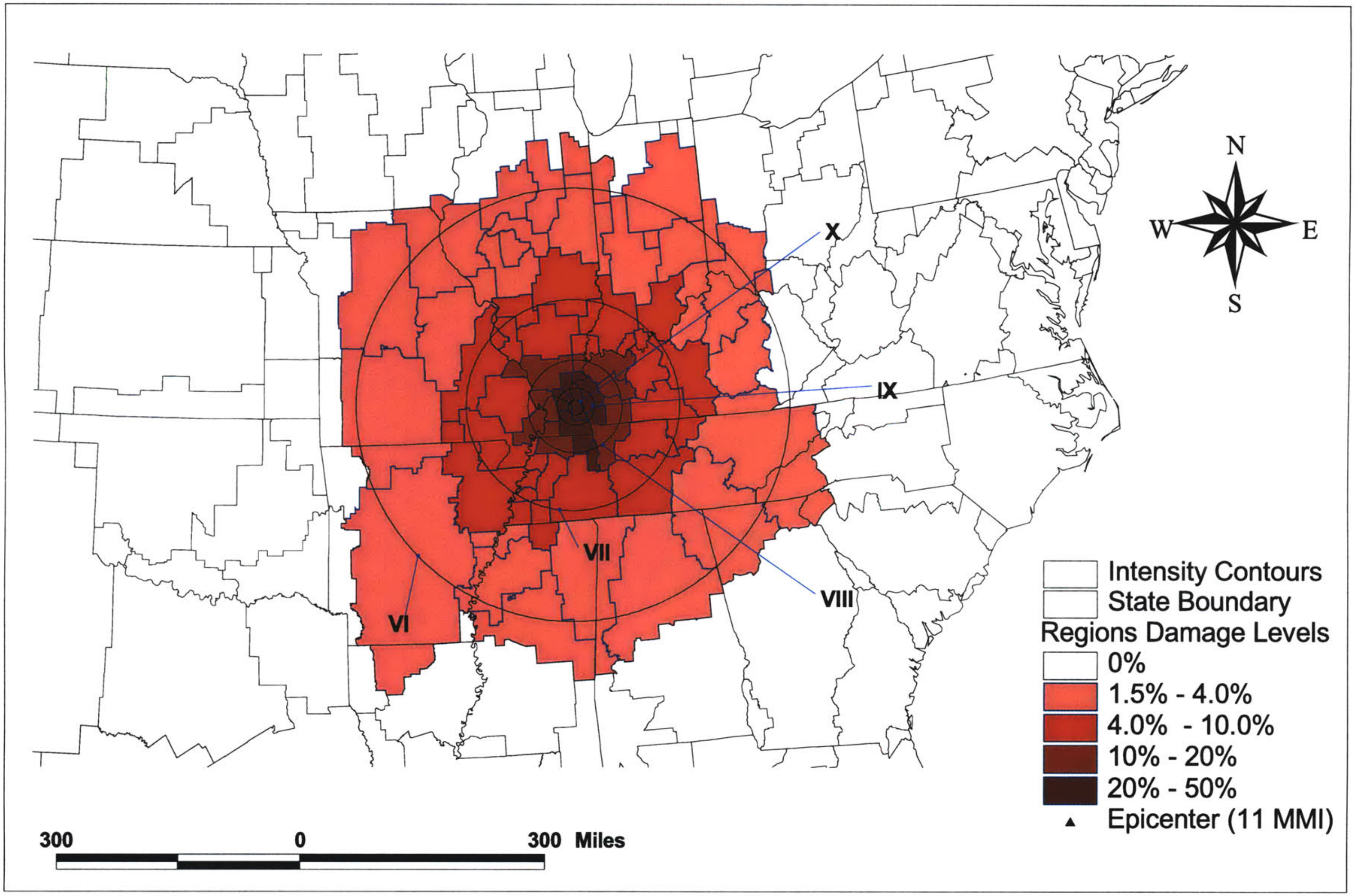

Figure 5-9: Initial damage to the "Food and Kindered Products" economic sector by region

Figure 5-10 shows the damage to the bridges in the affected region. Initial functionalities of bridges due to this damage is shown in Figure 5-11. These functionalities are restored over time using the ATC-13 Applied Technology Council (1985) restoration curves (also see Section 4.2.3), and Figure 5-12 illustrates the functionality after 21 days.

Figure 5-13 shows the functionality of the highways, reduced due to pavement damage. This damage to highway pavements causes initial loss of functionality across the region. However, unlike bridges that need repairing and rebuilding, most highways can be re-paved to restore functionality quickly. Figure 5-14 shows the functionality of links based on pavement damage 6 days after the earthquake.

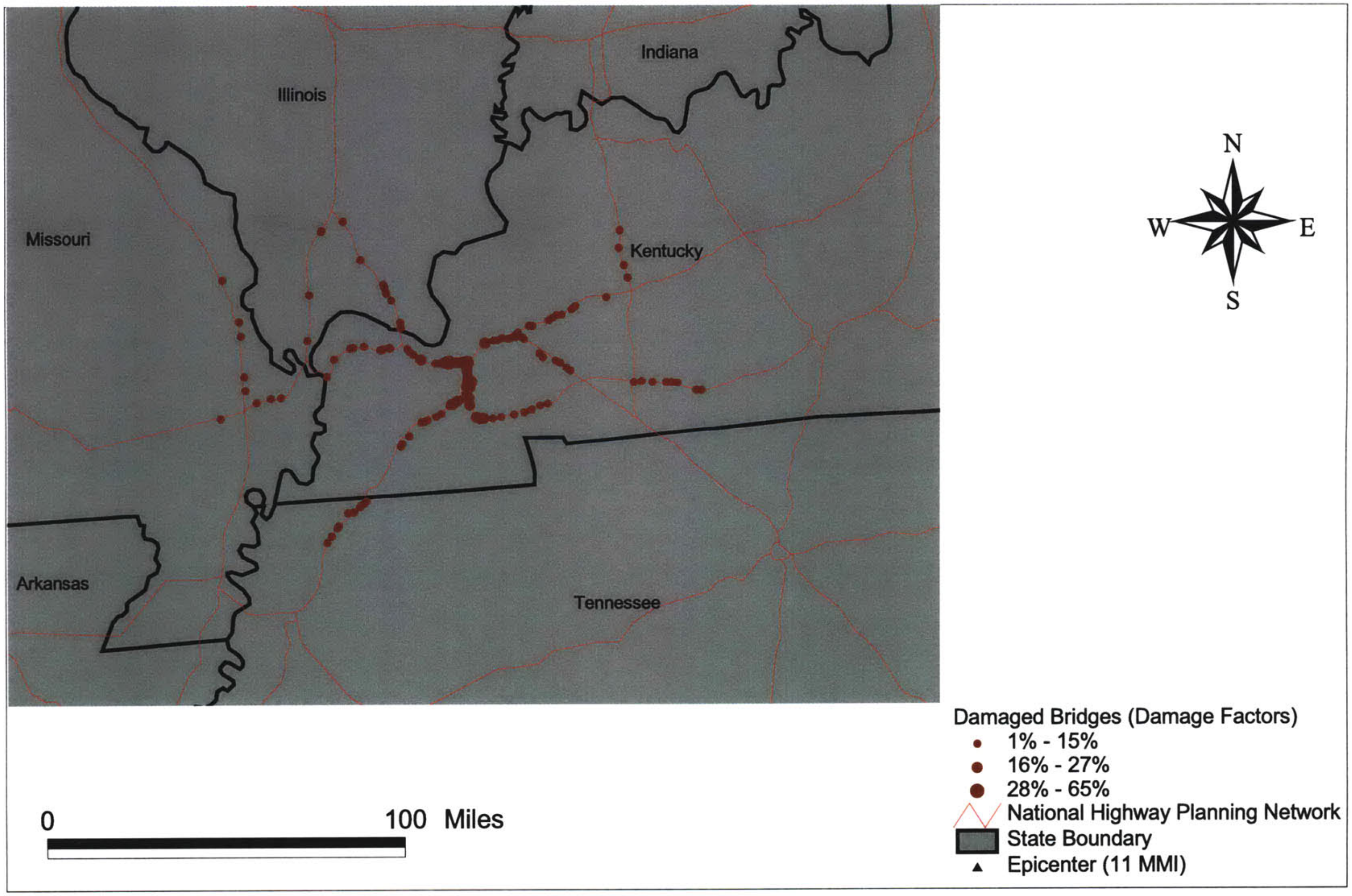

Figure 5-10: Initial bridge damage

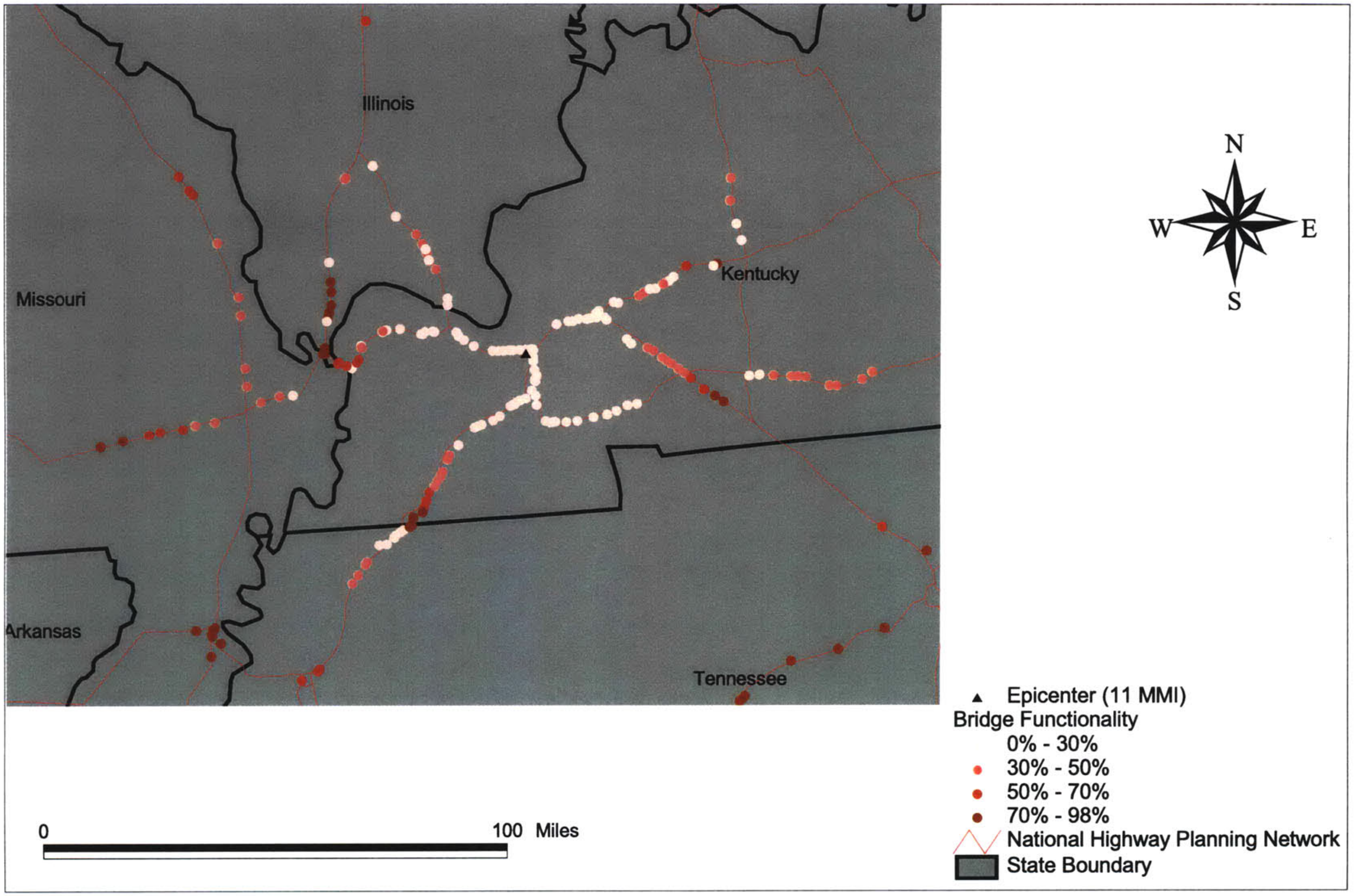

Figure 5-11: Bridge Functionalities at day 1

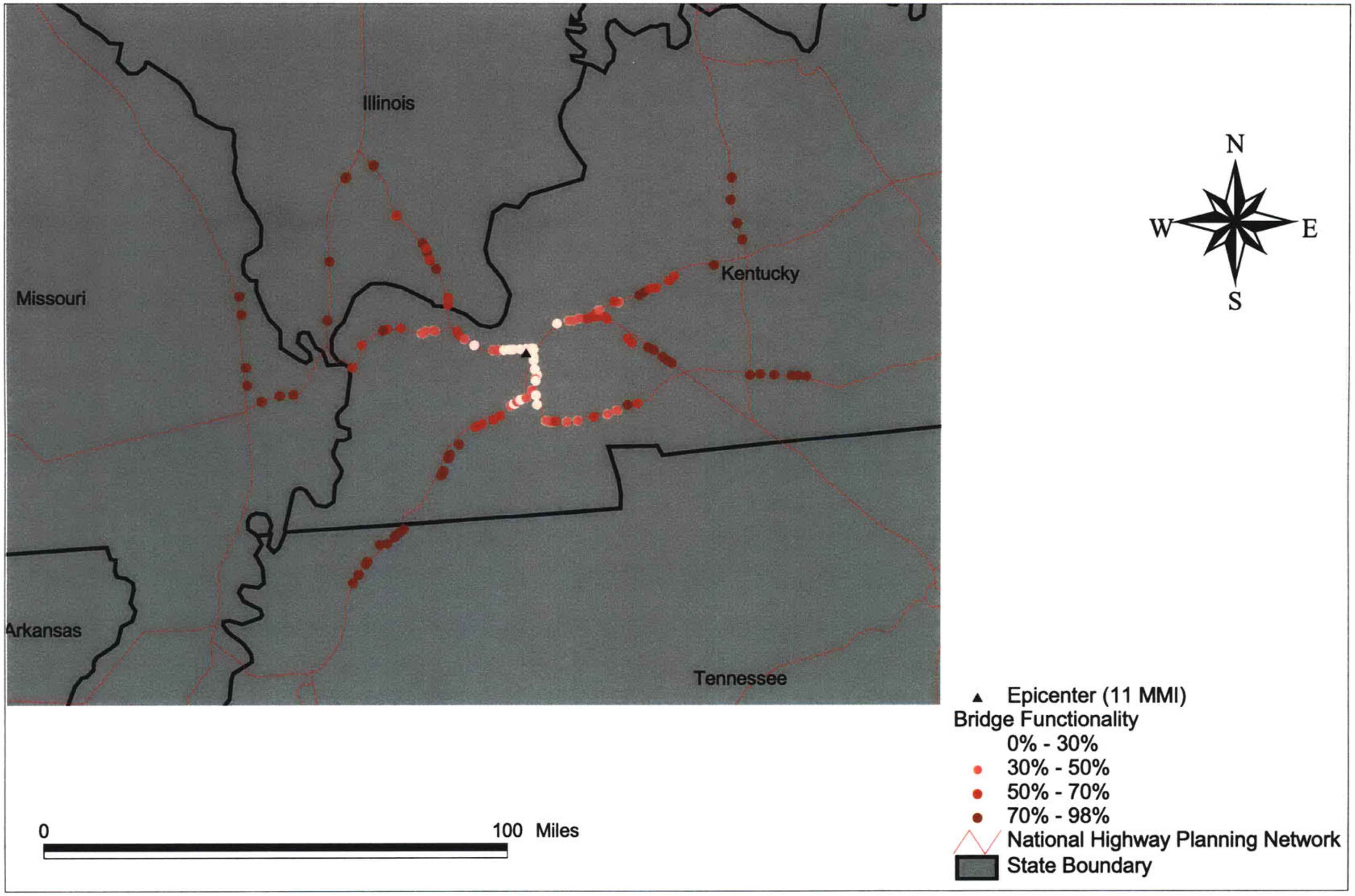

Figure 5-12: Bridge Functionalities at day 21

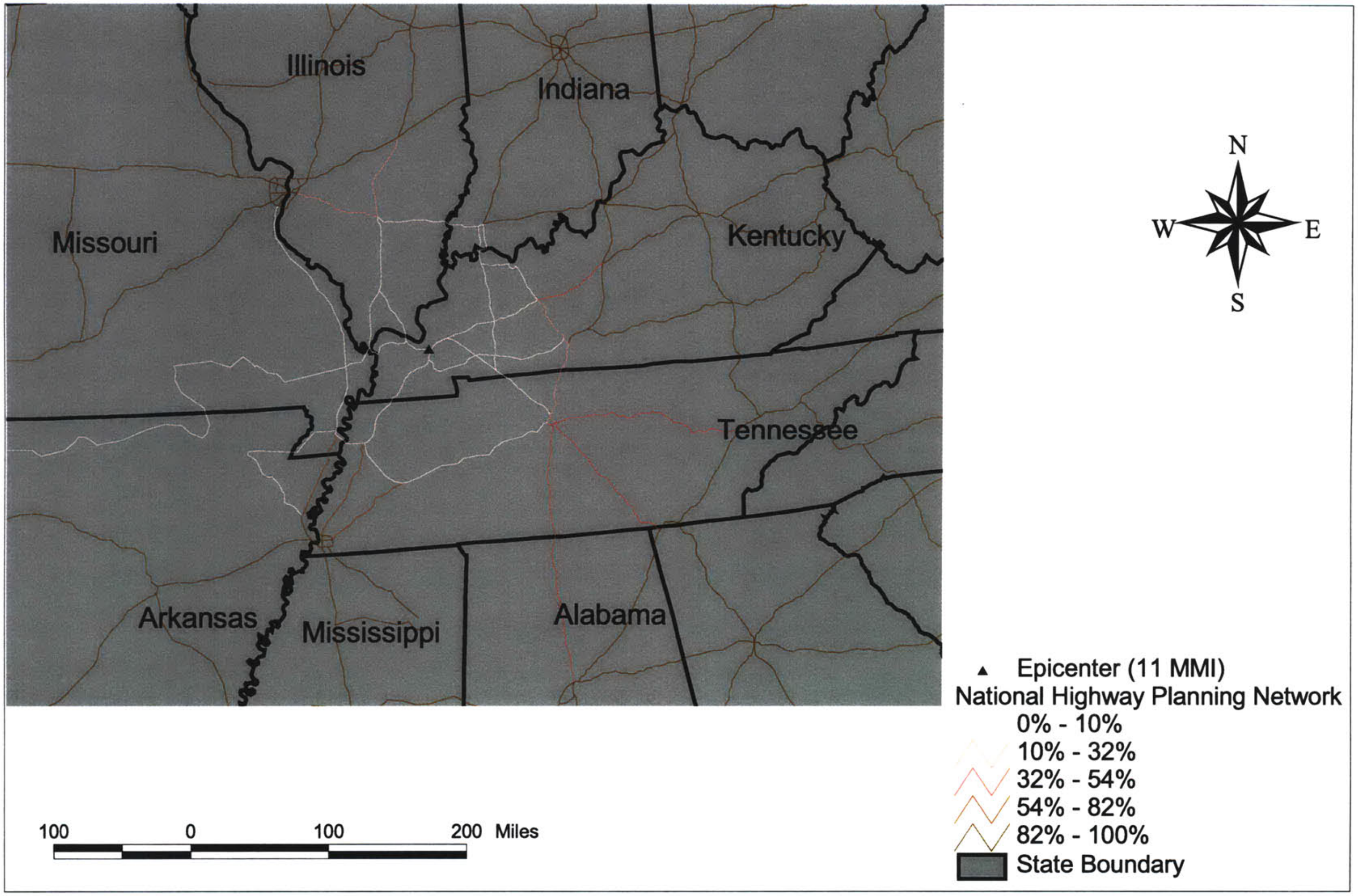

Figure 5-13: Link Functionalities at day 1

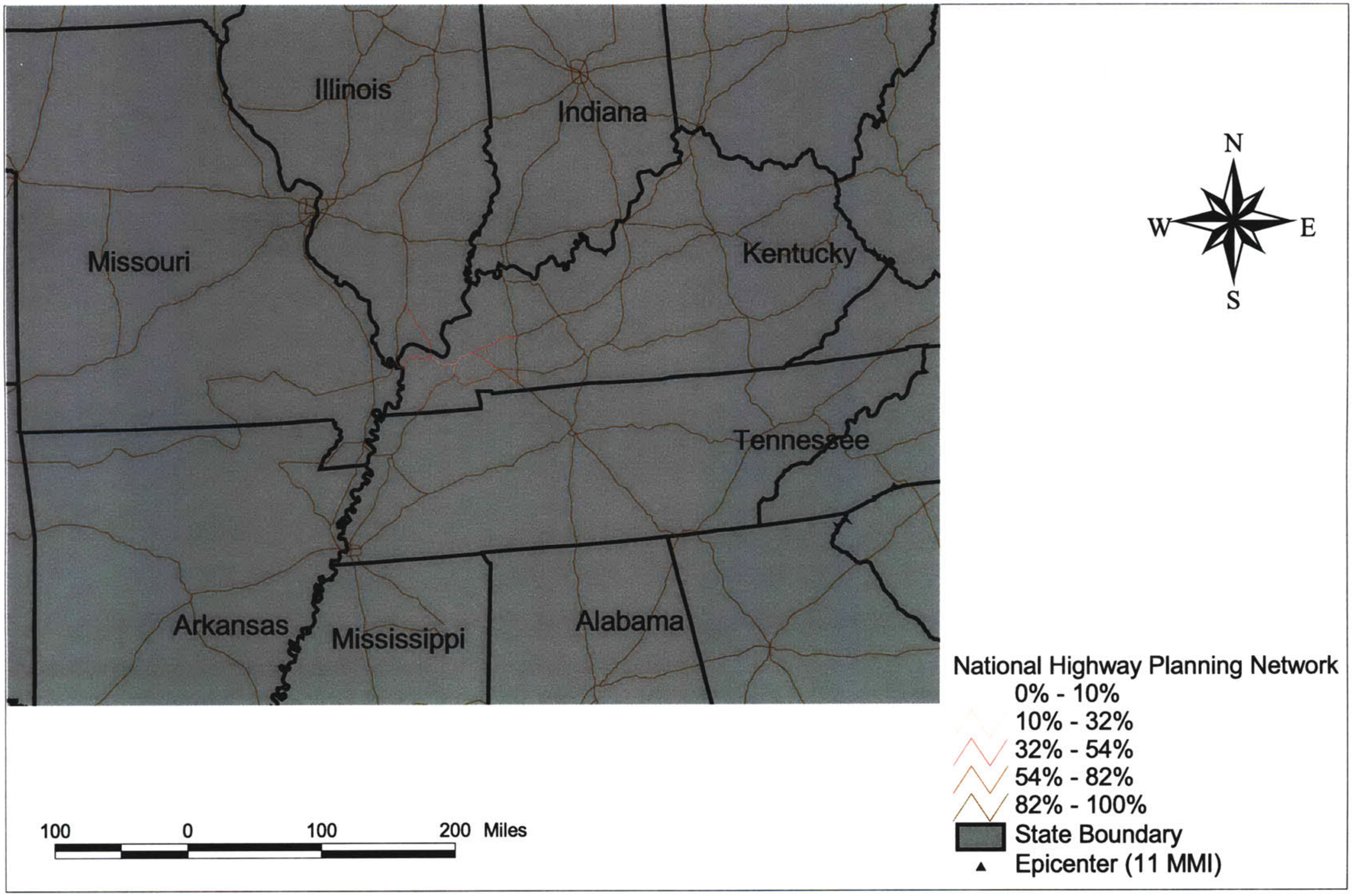

Figure 5-14: Link Functionalities at day 6

Figures 5-15 and 5-16 illustrate the functionality lost by the "Food and Kindered Products" and "Primary Metals" economic sectors in the affected regions immediately after the earthquake. The Food and Kindered Products industry has a greater proportion of facilities operating in structures of unreinforced masonry (UM). The Primary Metals industry on the other hand is a heavy industry, with most of the facilities of Heavy Steel type of construction 4.5. Thus, the Heavy Industry shows less damage and loss of functionality compared with the Food and Kindered Products industry. These functionalities reflect the actual production levels, and are achieved after calculating interactions and network constraints.

Figures 5-17 and 5-18 illustrate the effect of interactions and network constraints. The "Mining" economic sector depicted in the map does not have a fragility associated with it. Thus, the maximum possible functionality of this economic sectors is unchanged after the earthquake. However, inter-nodal network constraints and damage to economic sectors, lifelines, and nodal-transportation network create limitations that make it impossible for the mining industry to function in regions very close to the epicenter.

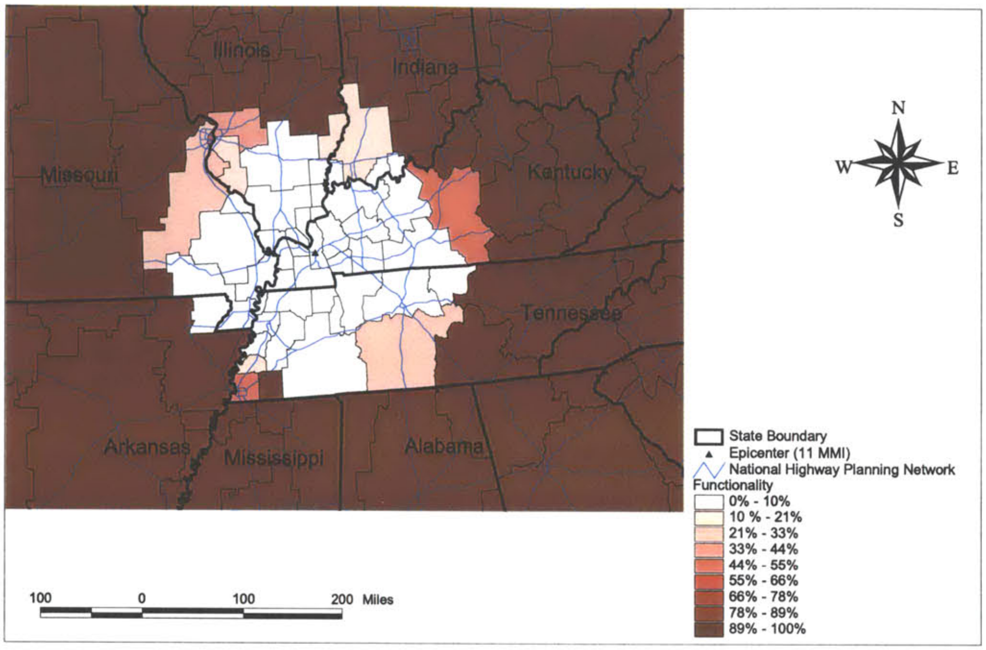

Figure 5-15: Initial functionality (post-earthquake) of the "Food and Kindered Products" sector constrained by the current functionality of other economic sectors, lifelines, and the transportation network

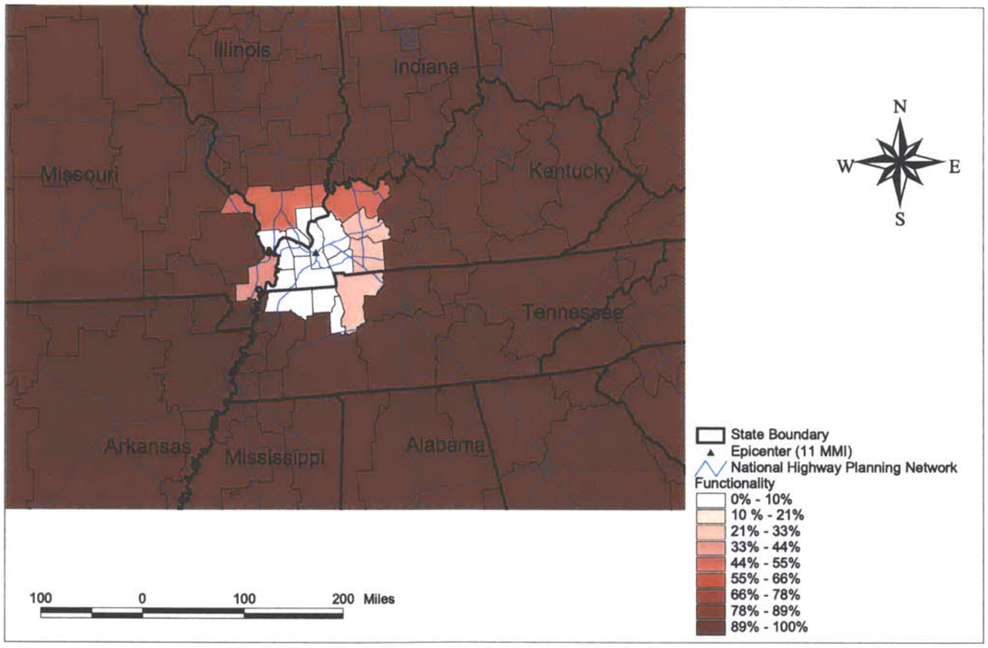

Figure 5-16: Initial functionality (post-earthquake) of the "Primary metals" sector constrained by the current functionality of other economic sectors, lifelines, and the transportation network

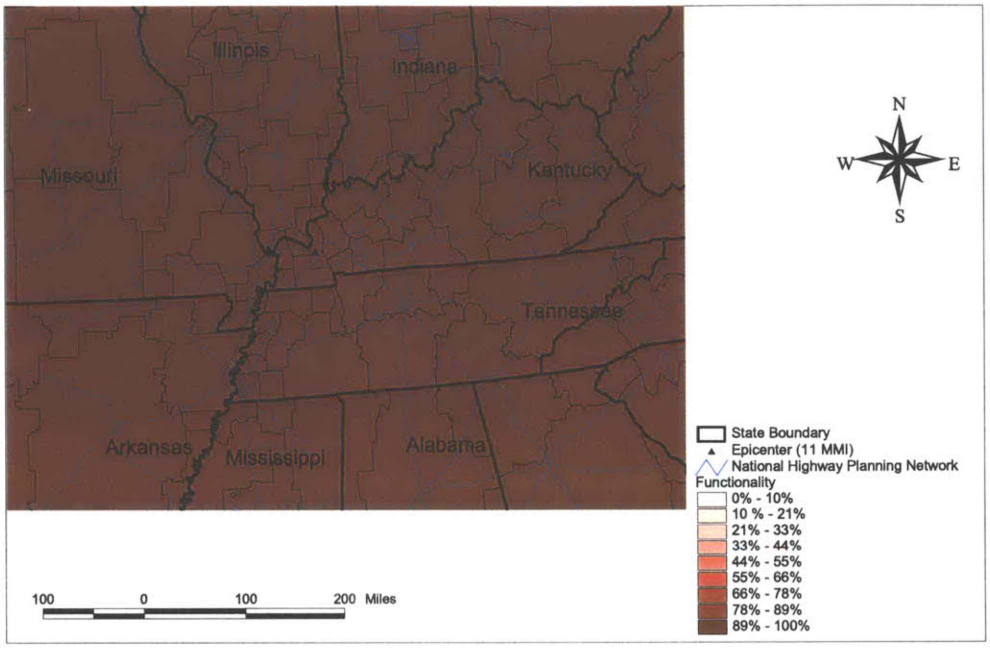

Figure 5-17: Maximum Functionality of the "Mining" sector (invulnerable) immediately after the earthquake (unconstrained by other economic sectors, lifelines or the transportation network)

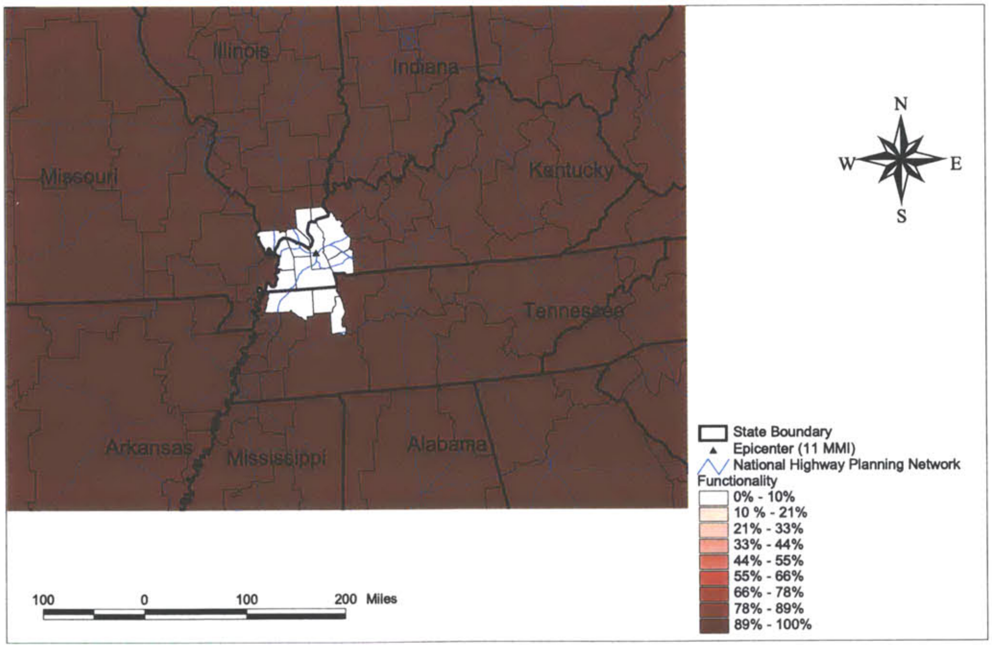

Figure 5-18: Functionality of the "Mining" sector constrained by the current functionality of other economic sectors, lifelines and the transportation network)

Figures 5-19, 5-20, 5-21, and 5-22 illustrate the production levels of the "Non-durables Manufacturing" sector in the earthquake affected region immediately, 6 days, 21 days, and 101 days after the earthquake. The functionality for the industry includes the effect of damage to itself and other industries related to it, damage to other infrastructure on the node (lifelines, transportation infrastructure, etc.), and the interregional transportation constraints. Thus, the functionality values represent the final functionality after all models and iterations in the discrete time step considered have been executed. The sector recovers over time and the industries closer to the epicenter that have sustained greater damage take longer to recover.

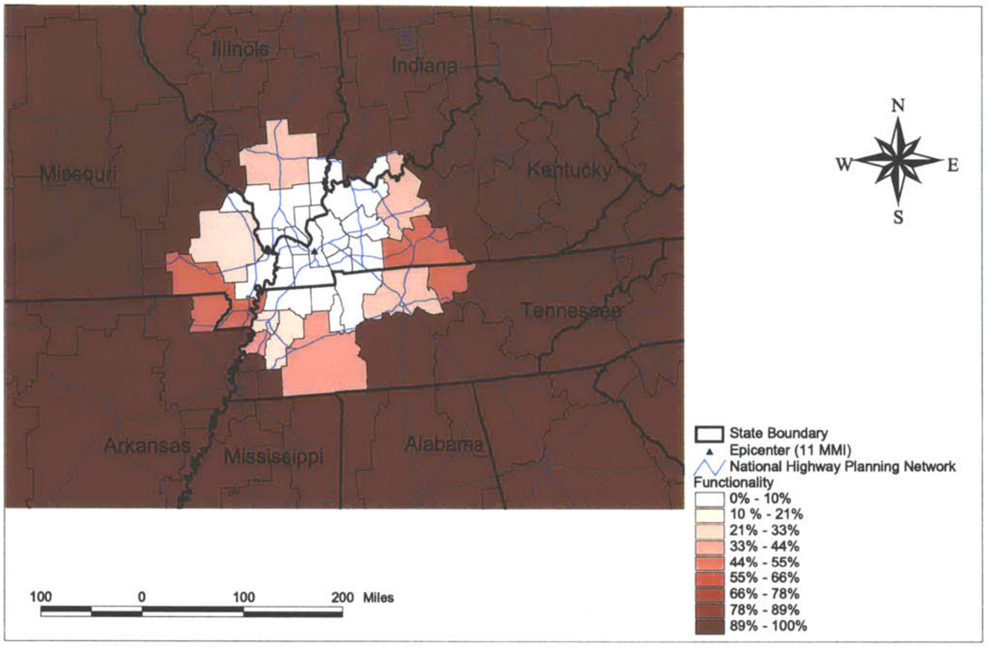

Figure 5-19: Functionalities of the Non-Durables Manufacturing sector immediately after the earthquake (constrained by other sectors, lifelines, and the transportation network)

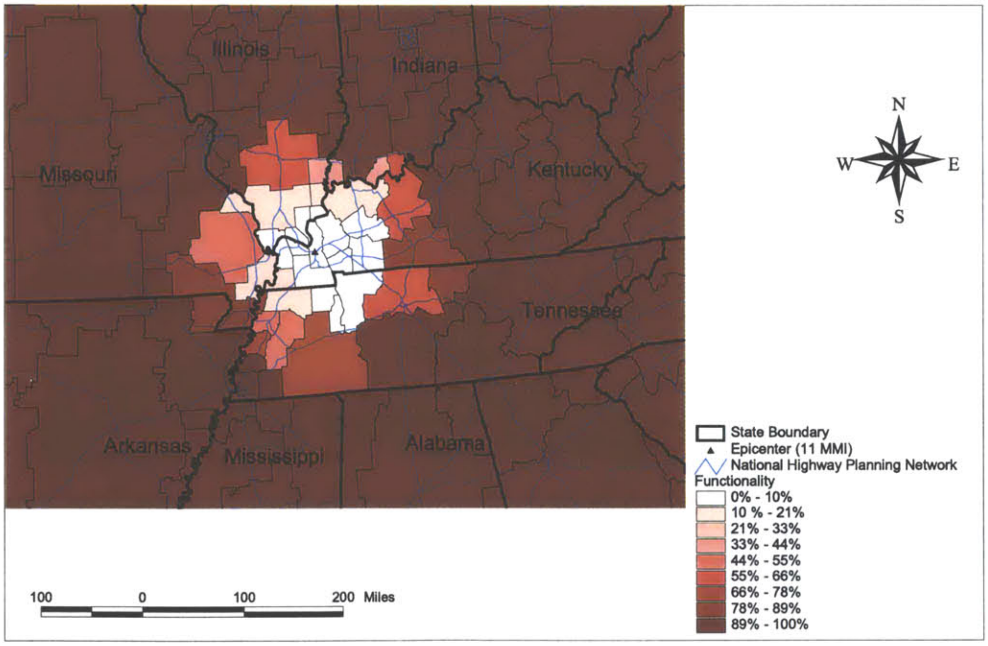

Figure 5-20: Functionalities of the Non-Durables Manufacturing sector 6 days after the earthquake (constrained by other sectors, lifelines, and the transportation network)

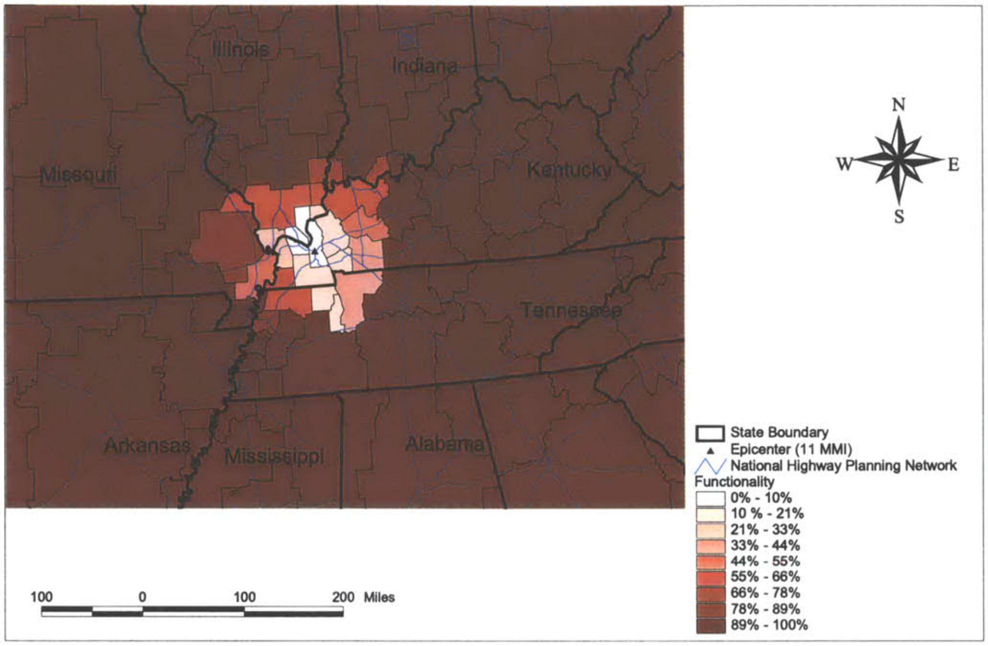

Figure 5-21: Functionalities of the Non-Durables Manufacturing sector 21 days after the earthquake (constrained by other sectors, lifelines, and the transportation network)

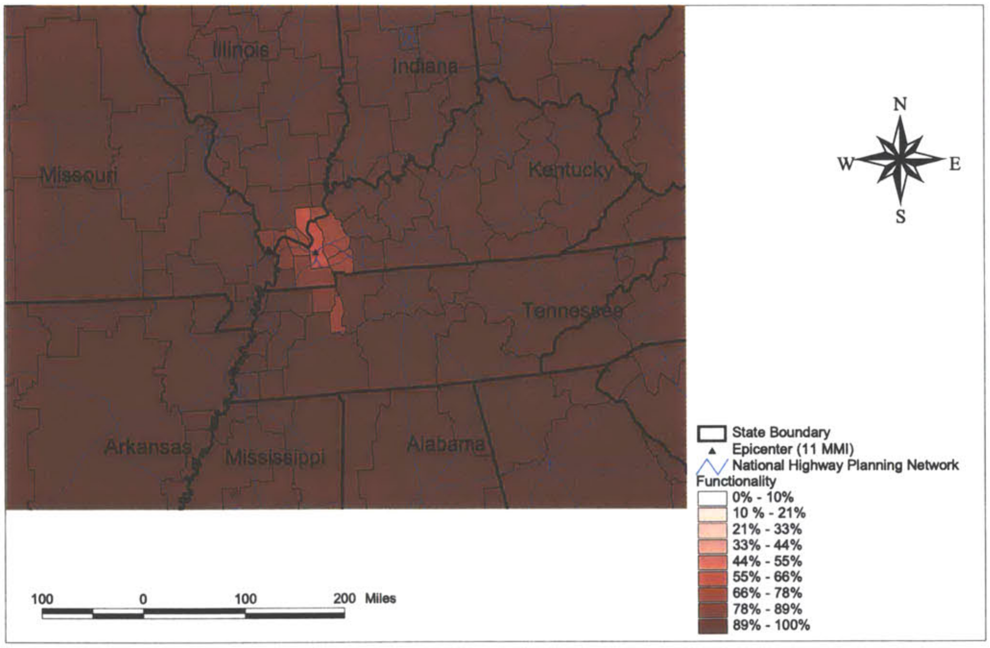

Figure 5-22: Functionalities of the Non-Durables Manufacturing sector 101 days after the earthquake (constrained by other sectors, lifelines, and the transportation network)

We now consider the effect of the transportation network damage on economic losses. Figures 5-24 and 5-23 summarize the effect of strengthening the interregional transportation system on the economy. The following cases are considered:

Transportation system *vulnerable*

> This is the normal case that considers damage to highway bridges and pavements (see Figure 5-10).

Transportation system *invulnerable*

> The transportation network is made *invulnerable* for the analysis. Thus, irrespective of the ground shaking intensities, none of the inter-nodal highway bridges or pavements are damaged. This case is an extreme case of transportation infrastructure hardening (e.g., through retrofitting of all bridges, etc.).

The losses and production levels for both cases are evaluated and compared. From Figure 5-23 (also see Table 5.4), it is clear that the transportation system constraint has the effect of reducing the overall production levels. The production levels depicted in the chart are aggregated over the entire nation. Also, the total levels as seen in Figure 5-23 take into account that the production levels have been increased globally (see Section 4.2.4) to nullify the deficit created by damage to production facilities in the affected regions. It can be seen, however, that there is a difference in the production levels with and without the network damage. Thus, it can be concluded that the reduction is a result of the transportation network constraint, and given a network *without* network damage, these production levels will be higher.

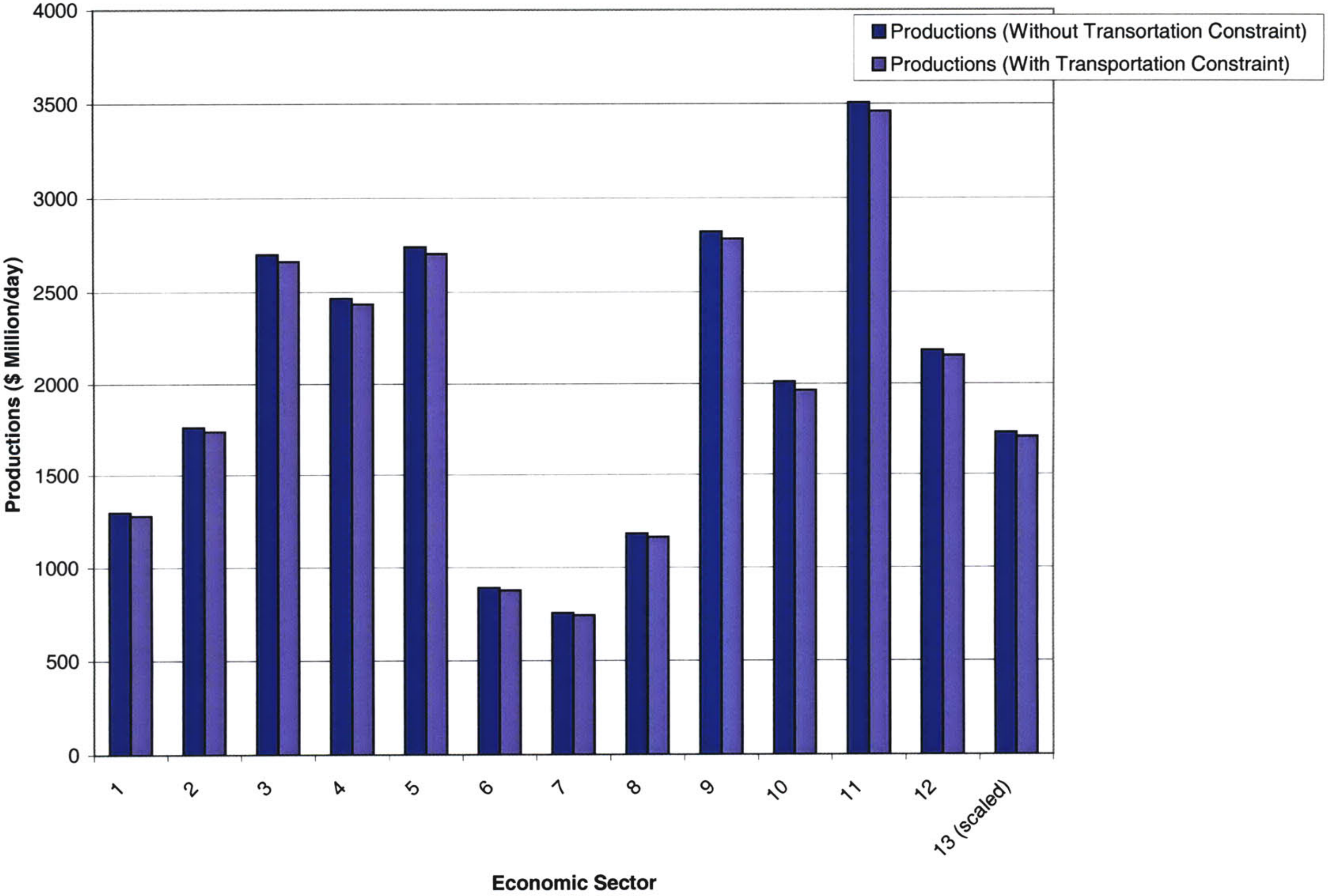

Figure 5-23: Final production levels over U.S. immediately after the earthquake, with and without transportation system damage (Note: The 13th economic sector has been scaled down by a factor of 10 to accommodate high variations in the chart)

Sector	Productions		Final Demands	
Sector	Without Transportation Damage	With Transportation Damage	Without Transportation Damage	With Transportation Damage
1	1295.404	1277.031	195.419	191.583
2	1762.151	1739.242	739.79	730.499
3	2700.378	2663.318	2084.519	2055.69
4	2464.68	2433.246	1733.755	1711.906
5	2739.486	2703.884	1499.175	1480.291
6	890.992	876.958	0	0
7	754.524	742.914	0	0
8	1180.453	1161.258	559.499	549.966
9	2821.084	2783.735	1902.623	1878.547
10	2009.501	1964.367	1469.585	1435.395
11	3505.998	3458.91	1145.645	1131.155
12	2182.496	2153.433	1235.57	1219.937
13	22498.547	22204.193	12868.054	12705.263

Table 5.4: Final production levels and demands with and without transportation network damage immediately after the earthquake ($ Million/day)

Figure 5-10 shows that several bridges in the directly affected region are damaged and initially have no functionality, leaving dysfunctional links and several isolated nodes, thus leading to shortages in the affected regions, or inability to export (or lowered production levels/final demands compared to pre-earthquake conditions).

The losses indicated in Figure 5-24 (also see Table 5.5) refer to the loss due to decreased production levels over the entire period of reduced functionality of components. As is clear from Figure 5-19 through 5-22, the industries take considerably longer to recover their functionalities than links in this scenario analysis. Thus, the difference in losses due to the presence or absence of highway infrastructure vulnerability is relatively small as in either case these network constraints are valid only for a small period of time. The effect of the constrained network is clearly felt initially when nodes may become inaccessible. Economic sectors 1, 2, and 3 do not have any earthquake vulnerability. Thus, the sectors experience insignificant amounts of losses if there is no transportation constraint. However, when vulnerability of highway infrastructure (highway bridges and pavements) is "switched-on", losses due to this lessened capacity are noticeable.

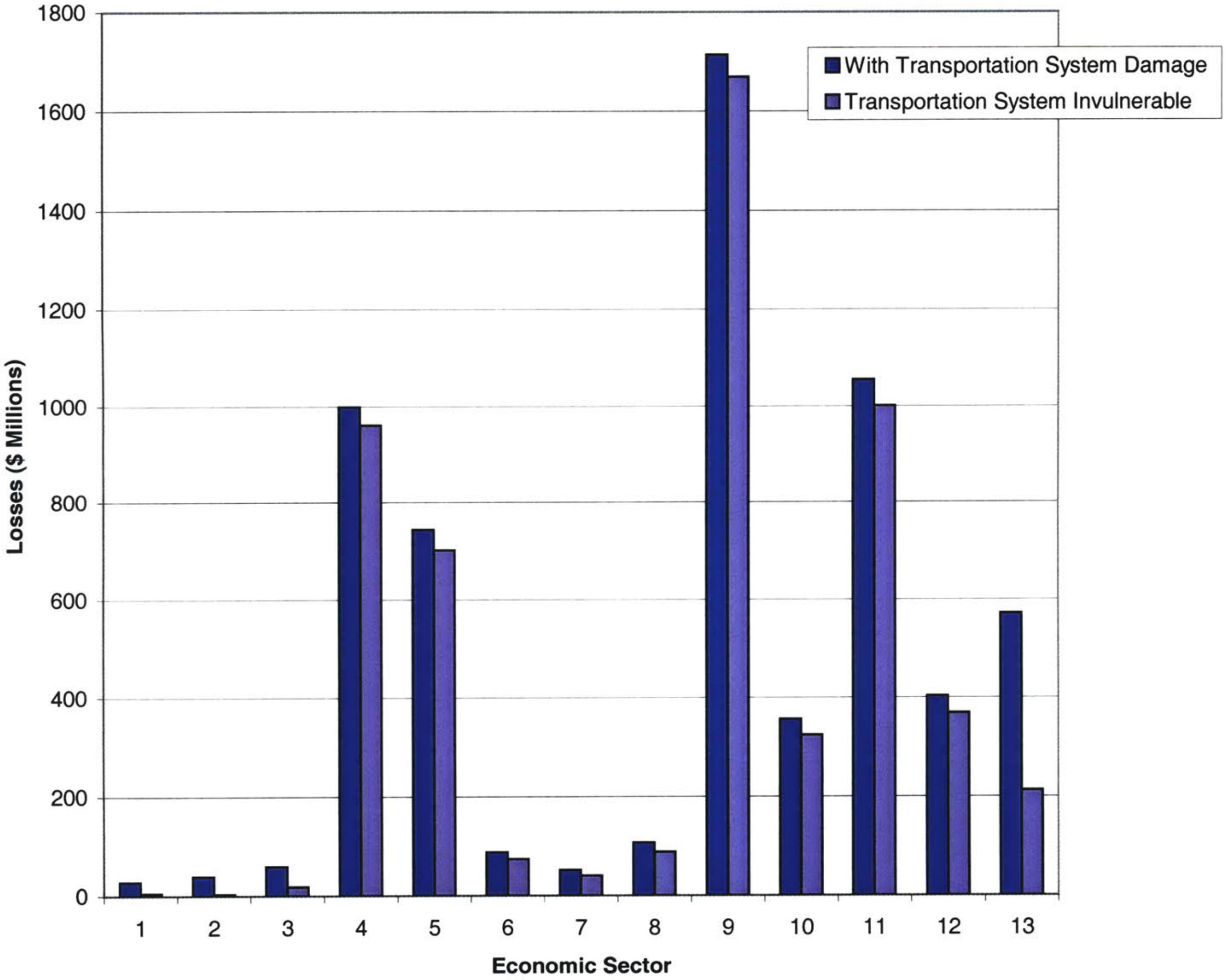

Figure 5-24: Business interruption losses (due to reduction in production levels of economic sectors), with and without transportation system damage over the entire recovery period

Sector	Losses with transportation network damage	Losses without transportation network damage
1	27.094	5.001
2	38.881	3.113
3	59.142	18.277
4	999.218	960.826
5	743.693	701.331
6	87.594	73.612
7	51.397	39.874
8	106.829	87.861
9	1713.038	1668.988
10	355.759	323.54
11	1055.27	1000.378
12	402.75	368.304
13	571.358	212.755

Table 5.5: Business interruption losses (due to reduction in production levels of economic sectors), with and without transportation system damage over the entire recovery period (in \$ millions)

Economic sector 13 (Commercial and Government) has a high output relative to other economic sectors (the 13th commodity is scaled by a factor of 10 in the Chart 5-24). Nevertheless, losses produced by this sector are relatively low due to its quick recovery. The difference in economic losses with and without transportation losses is however very high (the loss is more than halved by the non-vulnerability assumption). In can be concluded from these figures that damage to transportation system is responsible for a high proportion of losses. While the 13th economic sector accrues losses, most of the transportation constraints are active, thus resulting in a high transportation-related loss component. However, with other economic sectors, the transportation system recovers much before the sectors recover. Thus, the interaction with the damaged transportation system is only for a limited period of time while losses accumulate, producing lower transportation-related losses.

From a real world perspective, the transportation system *does* take considerably longer to recover than other systems (see, Figure 1-1). The models do not consider several factors including the limits in reconstruction capacity (several bridges damaged in a region cannot all be reconstructed at the same pace), and variability in damage (some bridges may be damaged extensively as against the *average* damage predicted by the models, making it impassable for several months, or even years). Thus, taking these factors into account, the losses may become considerable. Figure 5-25 shows the difference in the losses with and without the transportation network considering that the restoration time for all bridges is three time that considered in the methodology. There is clearly a higher difference in the two cases, indicating that the transportation-related losses can be higher, given that restoration of the transportation system is not as quick as predicted by contemporary studies. The concluding chapter discusses such issues and the scope for further work to improve the loss estimation capabilities of the methodology presented.

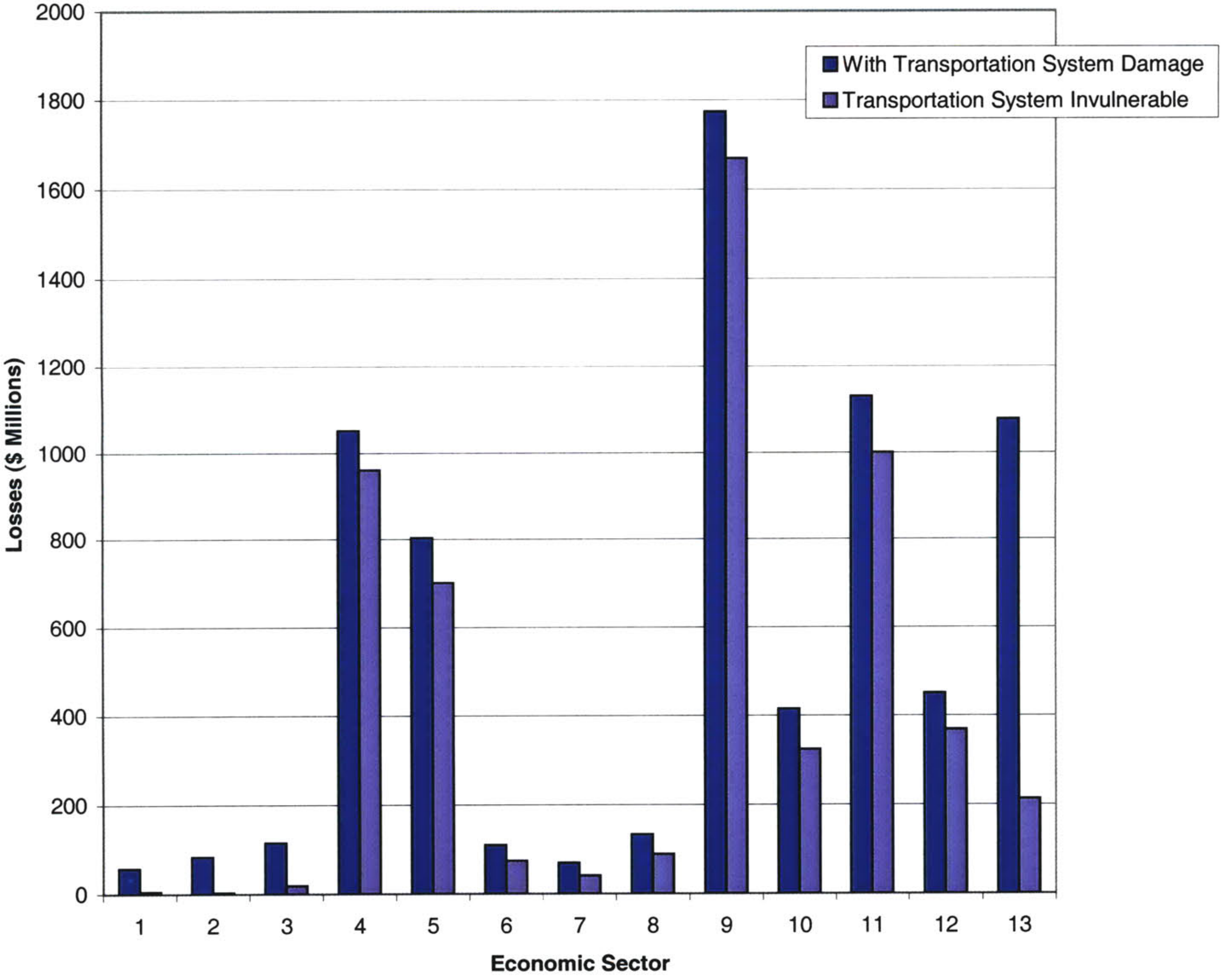

Figure 5-25: Business interruption losses (due to reduction in production levels of economic sectors), with and without transportation system damage over the entire recovery period; recovery time is 3 times the normal

Chapter 6

Conclusions

6.1 The Model

The methodology presented in this thesis integrates engineering and economic models of earthquake loss estimation, emphasizing the effect of transportation network damage. The methodology includes damage to industries, residential facilities, lifelines and the transportation network as a part of the loss estimation procedure. These components are related to each other, and interact in a complex framework where the level of functionality of one component may influence the performance of others. Such an integrated approach to earthquake loss analysis has been attempted by only a few researchers, and most previous studies have limited the scope of earthquake loss analysis to a few components.

Interactions are at two levels: (1) a local scale, and (2) an inter-regional scale. The local interactions are modeled non-spatially in the methodology, whereas the inter-regional interactions are modeled by the transportation network. The local scale interactions include disruption of lifelines and local transportation damage at the metropolitan scale. In reality, these interactions also have a complex spatial dimension, which in the present methodology is ignored. Activities in different economic sectors at various geographical "nodes" interact through their imports and exports carried over the inter-regional transportation network. The analysis includes damage to individual components of this inter-regional transportation system, consequently introducing constraints on the network capacity that disrupts the commodity flows between regions. Through this two level analysis (nodes and network), it is possible to have a quantitative understanding of the global effects of an earthquake. Previous earthquake loss studies have inadequately addressed the inter-regional spatial interactions and taken a more local geographical perspective. The studies that have included inter-regional exchanges have often lacked engineering models of earthquake damage and loss of function following the earthquake.

Ideally, local and inter-regional interactions should be modeled simultaneously. However, the resulting optimization problem is extensive and computationally challenging. Thus, a two step process is adopted, wherein the local interactions produce levels of imports and exports for each node, and then the transportation network is analyzed to produce optimal flows under these imports/exports. An iterative approach is used to satisfy both nodal and network requirements.

The methodology explicitly considers the functionality restoration process after the earthquake. This restoration is based on interactions and current functionalities of the various components at a given point of time after an earthquake. The restoration model therefore predicts the "system functionality state" at different times after an earthquake. The losses are calculated at discrete time intervals to account for this gradual recovery of the system. This is another important feature of the present model.

At the present stage, the methodology does not include many important features. For example, the methodology does not include local site conditions when calculating ground shaking intensities, the variability in seismic performance of individual structures that belong to a given vulnerability class, cross-hauling in the transportation network, and uses a coarse spatial discretization and coarse classifications of buildings, bridges, lifelines, and the economic sectors. Within these limitations, the methodology provides a framework for understanding the components of earthquake economic loss, and the sensitivities of the losses to various model parameters. It also provides a modular framework where improved models of earthquake ground motion, damage, loss of function, transportation and economics can be integrated.

Through sensitivity analysis, parameters that are important for accurate loss estimation and factors that are inconsequential can be differentiated (see Section 6.3 for a list of these factors) and alternative loss mitigation strategies can be compared.

6.2 Scenario Earthquake Application

The New Madrid scenario earthquake application presented in Section 5 serves as a "proof of concept" for the methodology. The results include direct and indirect losses from the hypothetical earthquake. They show that the transportation-related losses are not isolated from the physical and economic infrastructure and are closely associated with the level of functioning of the overall economy. As industrial facilities are damaged, the production and consumption levels are reduced. Thus, demand for the transportation system is also reduced. On the other hand, network damage creates constraints that cause shipping problems, and consequently reduce the productivity of economic sectors.

A way to assess the effect of reduced transportation capacity is to perform a sensitivity analysis to the earthquake vulnerability of the transportation system. The losses from a scenario that assumes a completely invulnerable transportation system are contrasted with those considering normal damage to the transportation system. In an initial base-case analysis, these transportation-related losses[1] were found to be modest. However, it should be noted that these losses were significantly subdued due to the assumption of deterministic fragility of bridges and pavements. By making the analysis deterministic, it is assumed that, when subjected to given earthquake intensity, all structures are damaged to the same *average* level. For example, *with* variability, some bridges on a highway would be damaged beyond repair and require several months of reconstruction before the highway can become operational, as opposed to the average damage (and quick recovery) predicted by the deterministic models in this methodology. Also, due to constraints in construction capacity and financial resources, it might not be possible to recover the functionality of *all* the

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[1] Found as a difference of losses in the two cases

damaged bridges at the rate assumed in the analysis[2]. A sensitivity analysis of losses with respect to recovery of the highway system has shown that the transportation network may actually be an important component of the total economic loss.

6.3 Future Research Directions

Further work in this area should address issues of sensitivity of losses to parameters and investigate methods to improve various components of the methodology.

The methodology developed in this thesis is coarse and simplistic in several respects. As is obvious from the broad scope of the methodology and the scenario, there are several data, computational and knowledge limitations that limit the accuracy of the results. There is a need to overcome these limitations. This should be preceded by an analysis of the importance of various parameters and model components. Parameters that are important can then be refined and emphasized.

Specific issues that should be addressed include:

Physical Organization

Optimal spatial resolution and spatial distribution of nodes and links through loss sensitivity analysis

Attenuation Model

The affect of site conditions/geology for attenuation and calculation of ground shaking intensities. Also, the uncertainty and analysis of earthquake intensity attenuation should be modeled.

Vulnerability Model

Sensitivity of losses to fragility and recovery parameters in the model

Inclusion of variability in the vulnerability of individual infrastructure elements (buildings, bridges, links, etc.)

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[2] Recovery curves have been extracted and refined from ATC-13 (Applied Technology Council, 1985)

Appropriate bridge classification and vulnerability/recovery models

Transportation Network Model

Calibration of results; for example, flows on the transportation network can be calibrated using available commodity flow survey data

Better transportation network models that include congestion parameters, cross hauling of commodities, passenger flow models, etc.

Economic Model

Parameters in the economic model, including those that control the distribution of deficit between population and industries in the nodes, and interaction coefficients for various economic sectors, residential buildings, lifelines, and the transportation system

Sensitivity of losses to economic sector classification and vulnerability classification

Quantification of other losses (or financial gains) such as the increase in production beyond the damaged regions to account for shortages, boost to the local economy through funding for reconstruction, etc.

The methodology can be extended to include earthquake risk analysis capabilities. Multiple scenario analyses can be performed and benefits of different loss mitigation strategies compared in this risk analysis framework. The methodology can finally be used as a tool to formulate effective loss mitigation strategies.

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