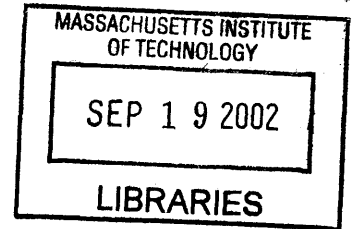


**Multi-Resolution Analysis of Earthquake Losses:
From City Block To National Scale**

ARCHIVES



by

Sumit Mathew Kunnumkal

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Transportation

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2002

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Abstract

This thesis advances existing methodologies to evaluate earthquake losses at local, regional and national scales. A specific application is developed for scenario earthquakes in the New Madrid region. The main issues addressed are:

1. Sensitivity of the estimated losses to formulation in terms of macroseismic intensity or quantitative ground motion characteristics
2. The effect of spatial resolution on the accuracy of the loss estimates

It is found that loss results are highly sensitive to the characterization of ground motion and moderately sensitive to the spatial resolution. Loss sensitivities to earthquake location, consideration of variability in damage from element to element and alternative structural classification systems are also investigated.

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Chapter 1

Introduction

The objectives of this thesis are to estimate earthquake losses at local, regional and national scales, examine the effects of the spatial resolution on the accuracy of the results and to compare the losses obtained using alternative characterizations of ground motion and damage (“macroseismic” vs “engineering” approaches, described in Chapter 2). Previous efforts to estimate earthquake losses such as Cho et al. (2000), Sohn et al. (2001a), Werner et al. (2000), HAZUS (2000) and Gupta (2001) (reviewed in Chapter 2) have not explicitly considered the issue of the accuracy of the results with the resolution of the model. Moreover, these methodologies adopt one of the two formulations to estimate earthquake losses. This thesis uses the work of Gupta (2001) as a base (reasons given later), advances it, and uses the revised methodology to estimate earthquake losses. Losses are found to be moderately sensitive to the spatial resolution and highly sensitive to the ground motion and damage characterization

Earthquakes cause widespread damage and losses. Losses due to earthquakes can be broadly classified into economic and social losses. Economic losses can be further broken down into direct, indirect and induced economic losses. There are direct losses due to damage to the infrastructure, indirect or business interruption losses due damage and/or economic interactions, and induced losses from secondary effects of earthquakes such as fires and flooding. Social losses are due to injuries, casualties, homelessness, reduced domestic consumptions and other psychological effects such as grief and trauma. While the quantification of these losses is important in order

to assess the seismic risk to a region and the effectiveness of various loss reduction strategies, it is not an easy task. Various factors pose challenges such as :

- Range of scales to be considered: The scale varies from local to regional to national. Different losses are prevalent at different scales. For example, the direct losses are more local while the indirect losses are more regional/national. Therefore, detailed modeling at the local level is required to accurately estimate the direct losses while a macroscopic methodology that operates at the national level is needed in order to estimate the indirect losses. In addition, there are difficulties in obtaining various data at the different scales. For example, the economic data, relating to the productions and domestic consumptions, is typically available only at regional or national level. On the other hand, geotechnical data, relating to ground failure etc., may be available only at a more local level.
- Effect of interactions : There are economic interactions among industries as an industry requires inputs and sells its produce to other industries and the population. These economic interactions translate into spatial interactions among regions, as a region is rarely self sufficient and imports (exports) commodities from(to) other regions. Thus, it is not possible to consider a component or region in isolation for loss estimation purposes. Losses have to be estimated from a global or system perspective. Again, there are computational issues in including all the loss components as well as difficulties in quantifying the different interactions.
- Presence of uncertainties : There are significant uncertainties in both parameters and processes. There are uncertainties in various parameters, due to lack of sufficient knowledge (epistemic). In addition, there are also uncertainties due to the inherent randomness in the process (aleatory). While these uncertainties affect the loss estimates, they are difficult to quantify and model.
- Transportation network analysis: The transportation network is an important

loss component as disruption of commodity flows leads to economic losses. However, the transportation network analysis requires complex optimization algorithms for routing commodities on the network. This restricts the size of the network as well as the number of commodities flowing on it. It is even more difficult to model network congestion (non-linear link travel times), passenger flows (OD flows) and multi-modal flows (road, rail, air etc.).

A number of trade-offs result. For example, there is the trade-off between the spatial resolution and the scale of the model - the finer the spatial resolution, the smaller is the scale at which the model can operate. There is the trade-off between the classification system and the uncertainties in parameters. For example, a very fine building classification reduces some of the uncertainty in the building fragilities, but it also introduces additional computational challenges. A coarse classification in which different building types are lumped in the same category is less computationally demanding. However, it introduces additional uncertainties since there are buildings with varying characteristics within the same category. There are similar trade-offs on the network side, where the size of the network is inversely related to the number of commodities flowing on it and the solution time.

Previous efforts illustrate some of these trade-offs. Some focus on the metropolitan or regional scale (HAZUS (2000), Shinozuka et al. (1998), Werner et al. (2000)). Others consider only certain loss components. Okuyama et al. (1999), Sohn et al. (2001a) focus on the macroeconomic effects of transportation network damage, Werner et al. (2000) deal with the increased travel times due to network disruption, Chang (1998) looks at the effect of electric-power network failure on the economy. Chapter 2 reviews some of these methodologies. While they represent important advances, addressing highly complex issues, these methodologies fall short of presenting an integrated, comprehensive view of the earthquake losses.

An integrated macroscopic earthquake loss methodology has been developed (Gupta (2001), reviewed in Chapter 2) to estimate the losses at the national level. The methodology accounts for damage to the physical infrastructure and loss-of-functionality, models the recovery of functionality over time and considers the inter-industry and

inter-regional interactions in evaluating the losses. Thus, Gupta (2001) presents a more “holistic” view of the losses compared to the other methodologies. However, it has certain drawbacks as well. For example, the loss model is deterministic and has a rather coarse spatial resolution and infrastructure classification system (fully discussed in Chapter 2).

In spite of its deficiencies, the methodology of Gupta (2001) is the only one which estimates the losses at a macroscopic level, considering the seismic vulnerability of infrastructure elements and modeling effects of disruption to the economic sectors and the transportation network in an integrated manner. Therefore, the methodology of Gupta (2001) is considered to be a good starting point for the purposes of this thesis and provides the foundation for this work. This thesis improves upon the methodology of Gupta (2001) (Chapter 3) and uses the revised methodology to estimate earthquake losses. Losses are evaluated for scenario New Madrid¹ earthquakes (Chapter 4). The New Madrid region is specifically considered because of the strategic importance of the Midwest region of the U.S. - it is an economically active region and a large fraction of the national commodity flows pass through the region (Okuyama et al. (1999)). Error in the loss estimates resulting from having a coarse spatial resolution is examined. Sensitivity of the losses to alternative modeling approaches and selected model parameters is also studied. Finally, loss reductions from various mitigation strategies are compared.

Chapter 2 reviews existing earthquake loss estimation methodologies. In particular, the methodology of Gupta (2001), which forms the basis of this work, is reviewed in detail and its deficiencies are pointed out. Chapter 3 describes the improvements made in the loss estimation methodology of Gupta (2001). Chapter 4 presents the numerical results obtained using the revised methodology for scenario New Madrid earthquakes. Chapter 5 summarizes the work and suggests areas for further improvement.

¹The New Madrid seismic zone lies within the central Mississippi Valley, extending from northeast Arkansas, through southeast Missouri, western Kentucky to southern Illinois. It was the epicenter of the great 1811-1812 earthquakes.

Chapter 2

Literature Review

This chapter reviews various earthquake loss estimation methodologies. First, a broad overview of various methodologies is given. Then, certain methodologies which are considered to represent the state-of-art in earthquake loss estimation are reviewed in greater detail. This includes the methodology of Gupta (2001), which forms the basis for this work. Deficiencies in the methodology are pointed out; the improvements made are discussed in Chapter 3.

Previous efforts can be broadly classified according to geographical scale, scope, and modeling approach.

- Geographical scale: Methodologies can be broadly classified as sub-metropolitan, metropolitan, regional or national on the basis of the geographical extent considered for evaluating the earthquake losses. Comerio (2000) evaluate losses at a sub-metropolitan level, in particular for UC Berkeley. Comerio (2000) evaluate the seismic hazards within the campus, determine the seismic vulnerability of individual buildings and develop estimates of repair times and replacement costs for individual buildings, on the basis of which direct and indirect economic losses are estimated. Cho et al. (2000) and Werner et al. (2000) (reviewed in detail later) evaluate losses at the metropolitan level, for the Los-Angeles and Memphis metropolitan regions, respectively. Rojahn et al. (1997) evaluate earthquake losses for Salt Lake County, Utah by updating, revising and

translating the ATC-13 (1985)¹ for application in Utah. Methodologies which have a greater geographical extent include HAZUS (2000), Sohn et al. (2001a) and Gupta (2001). HAZUS (2000) is an example of a regional loss estimation methodology while Sohn et al. (2001a) and Gupta (2001) examples of methodologies which operate at the national level.

As noted in Chapter 1, there is the trade-off between the geographical scale of the methodology and the spatial resolution. At smaller scales it is possible to have a high spatial resolution, while for larger scales, numerical feasibility and data intensiveness limit the degree to which the resolution can be increased. For example, while Cho et al. (2000) operate at the level of traffic analysis zones within the Los-Angeles metropolitan region, the county is the lowest geographical unit in Gupta (2001).

- **Scope:** The scope of a methodology includes the loss elements considered and the losses evaluated. Most methodologies focus on a particular loss component. Rojahn et al. (1997) and HAZUS (2000) focus mainly on the losses from building damage. Sohn et al. (2001a) and Werner et al. (2000) consider the losses from transportation network damage. There are a number of studies which look at the effects of lifeline disruption. For example, Rose et al. (1997) estimate the regional economic impacts of electricity lifeline disruptions caused by earthquake damage. The emphasis is on quantifying the economic losses resulting from businesses being cut off from electricity service; property damage is not considered. Chang (1998), Schiff (1998) and Rose and Benavides (1998) are examples of other studies which look at the economic impacts of electricity distribution network disruption. Eguchi (1994) evaluates the seismic vulnerability of 3 oil pipeline systems in the New Madrid region and estimates the social, economic and environmental impacts caused by failure of this system. To the best of our knowledge Cho et al. (2000) and Gupta (2001) are the only

¹Applied Technology Council's ATC-13 (1985) report includes expert-opinion damage and loss of functionality estimates for facilities in California

ones that present an integrated view of the losses by considering the disruption to the economic sectors in conjunction with the transportation network damage. Gupta (2001) also models the effects of lifeline damage, albeit in a very coarse manner.

- **Modeling approach:** Alternative modeling approaches include the “macroseismic” and “engineering” approaches. The “macroseismic” approach is defined as the more qualitative, judgmental approach to earthquake loss estimation, with the intensity unit based on observed damage levels, attenuation relations² derived from historical records of earthquake damage and fragility curves³ usually based on expert-opinion. Earthquake losses have been traditionally estimated using the macroseismic approach. The engineering approach is more quantitative and more recent, with parameters based on instrumental recordings and engineering analysis. Gupta (2001) and Rojahn et al. (1997) are examples of methodologies that follow the macroseismic approach. National Institute of Building Sciences (2000), Sohn et al. (2001a) and Werner et al. (2000) are examples of methodologies that follow the engineering approach.

The methodologies of Sohn et al. (2001a), Cho et al. (2000), Werner et al. (2000), HAZUS (2000), and Gupta (2001) are representative of the different classifications(scale - metropolitan vs regional vs national; scope - single component vs comprehensive loss estimation; modeling approach - macroseismic vs engineering approach); they also represent the state-of-art in earthquake loss estimation. These methodologies are reviewed next in greater detail.

Sohn et al. (2001) Sohn et al. (2001a,b) extend the methodology developed by Okuyama et al. (1999). The objective is to evaluate the macroscopic economic losses due to transportation network damage. The losses include reduced final demands and increased transportation costs. 36 earthquake analysis zones

²used to calculate ground motion intensity as a function of distance

³used to characterize the seismic vulnerability of a facility

(EQAZs) and 13 commodity classes are considered in the analysis. The earthquake analysis zones are the centers of economic activity. Sohn et al. (2001a) focus their analysis on the Midwest region. Therefore, they divide 9 Midwestern states : Illinois, Indiana, Iowa, Michigan, Missouri, Kentucky, Ohio, Tennessee and West Virginia into 29 analysis zones. On average, there are 2-5 EQAZ's per state. The rest of the U.S. is divided into 7 macro regions. The transportation network is represented by the US highway and primary rail systems. Final demands are estimated for each commodity in each EQAZ for a 25 year time period starting from the year 1993. Based on the year of occurrence of the earthquake, which is one of the parameters in the scenario analysis, appropriate final demands are used. Following the earthquake, the decrease in final demand due to network damage is calculated as a function of the resiliency of the economic sector and the network disruption ratio. Resiliency of an economic sector is defined as the fraction of production remaining after complete disruption of the transportation network, and is estimated for each sector by considering the proportion of intrazonal flow and highway flow and the average shipment distance. The network disruption ratio for a region is calculated as the ratio of the damaged link(s) capacity between zone i and all adjacent zones to the undamaged link(s) capacity. The disrupted link capacity is calculated based on bridge damage alone; pavement damage is not considered. An integrated commodity flow model (ICFM), which combines a multi-regional input-output model with a commodity flow model, is used to estimate the flows between the analysis regions and to allocate them to the transportation network. A regional input-output model is used to determine a region's net exports, taking into account inter-industry interactions. A commodity flow model is used to allocate the net exports to the transportation network at the minimum cost. The ICFM combines these two models and solves both problems simultaneously. Scenario results are presented for an $8m_b$ New Madrid earthquake in the year 2001. Sensitivity analysis is also carried out to determine the critical links in the network. Two types of sensitivity analyses are performed, one in which the link of interest

is assumed to be completely damaged while all the other links are undamaged and the other in which all links except the link of interest suffer damage. Links which cause a greater increase in the total loss per unit damage are considered to have higher retrofit priorities.

The methodology developed by Sohn et al. (2001a) models the economic input-output system and flows on the transportation network in considerable detail. Network congestion is modeled using non-linear link travel times. This methodology models the dispersion of flows or crosshauling, thus making the network model more realistic. It is also unique in modeling multi-modal flows, considering both the highway and rail networks. However, the seismic vulnerability of the economic sectors is not modeled. The reduced production capacity of the economic sectors due to damage, and the resulting decrease in the transportation demand is therefore not taken into account. The recovery process is also not modeled in detail - links are assumed to be in the damaged state during the analysis period, which is taken to be 1 year.

Cho et al. (2000) The methodology of Cho et al. (2000) operates at a metropolitan/sub-metropolitan level. It is a very comprehensive methodology, in which the economy of the region and the transportation network are modeled in an integrated manner. This is done by integrating a bridge performance model, network model, regional input-output model and spatial allocation model. The losses evaluated are the direct losses due to infrastructure damage and the indirect losses due to business interruption and increased transportation costs. The analysis focusses on the Los Angeles metropolitan region, which is divided into 308 sub-regional zones, mainly municipalities. 17 economic sectors are considered. The methodology uses data from a wide variety of sources including the Regional Science Research Institute (RSRI) input-output model of the Los Angeles metropolitan economy, the 1994 transportation planning network based on data from the Southern California Association of Governments (SCAG) and California Department of Transportation (CALTRANS) Headquarters and the

1991 SCAG Origin-Destination Survey data. Structural damage and the resulting direct losses are obtained using EQE's EPEDAT software. EPEDAT also provides estimates of the loss-of-function of the economic sectors and the length of time during which they are non-operational. These are used to calculate the reduced productivity of the businesses. A series of iterations are carried out to allocate the indirect losses in a manner that is consistent with the travel demand and network costs following the earthquake. Scenario results are given for a $7.1m_b$ earthquake on the Elysian Park blind thrust fault in Los Angeles. Sensitivity results are also given for alternate bridge repair strategies namely repairing bridges in ascending and descending orders of pre-earthquake traffic. The methodology of Cho et al. (2000) is one of the few that model both the economy and the transportation network in an integrated manner, and thereby captures both the reduction in demand as well as capacity of the transportation system following the earthquake. The transportation model is rather detailed. Cho et al. (2000) model passenger and freight flows and network congestion. However, there are some aspects that are rather coarsely modeled. While the recovery of the economic sectors is considered, the same is not done for the transportation network. The network is assumed to be in the damaged state for a period of one year. Moreover, partial closure of bridges is not allowed in the model. The model assumes that each bridge is either open or closed, depending on whether the bridge damage is greater or less than a given damage index. The methodology also does not consider the impact of damage to households on the losses. The data intensiveness and computational complexity restricts the methodology to a microscopic scale. Specificity to southern California and use of proprietary models also limits its general applicability.

Werner et al. (2000) Werner et al. (2000) have developed a methodology to evaluate the direct and indirect losses due to damage to the highway components. The methodology operates at the metropolitan level. It incorporates four modules namely the system module, the hazards module, the component module,

and the economic module. The system module has data on the network topology, the locations of the O-D zones, and O-D trip tables. It uses a technique from the Artificial Intelligence field called the Associative Memory (AM) approach to approximate flows on the network, as opposed to using conventional network analysis. This is done in the interest of computational tractability. The hazards module includes source models, attenuation relations, liquefaction data and data on local soil conditions. The component module is used to calculate the damage, the loss of functionality and the subsequent recovery of the network components. Bridges, approach fills, and pavements are the components considered in the analysis. The economic module is used to evaluate the losses from the earthquake. The direct losses are due to network damage. The indirect losses include the cost of travel delays and increased fuel costs due to these delays. The increased access and egress times to/from the various O-Ds are also obtained. The methodology provides the option of carrying out a deterministic or probabilistic analysis. Uncertainties in earthquake location, magnitude, ground motion and component fragilities are incorporated into the methodology. Probabilistic loss estimates can be obtained by carrying out a number of simulations in which the earthquake location and magnitude, ground motion intensity and transportation network damage are random variables . Results are given for scenario earthquakes near Memphis, Tennessee.

The methodology of Werner et al. (2000) captures the system effects of transportation network damage. In contrast to the methodologies of Sohn et al. (2001a) and Cho et al. (2000), the recovery of the transportation network over time is modeled. By including uncertainties in the various parameters, the methodology has the ability to carry out a seismic risk analysis of the highway system. However, this methodology does not consider the seismic vulnerability of economic sectors, residential dwellings or other lifelines. As a result, the methodology does not account for the reduced demand for the transportation system post-earthquake. The applicability of the methodology beyond the metropolitan scale is limited by its data intensiveness and computational re-

quirements.

HAZUS (2000) HAZUS (2000) is a regional loss estimation methodology developed by the Federal Emergency Management Agency(FEMA) under a cooperative agreement with the National Institute of Building Sciences. It is nationally applicable with extensive default databases for all states at the census tract level. The methodology includes 6 interdependent modules namely Potential Earth Science Hazard(PESH), inventory, direct damage, induced damage, direct losses and indirect losses modules. The PESH module estimates ground motion and ground failure. The inventory module describes the physical infrastructure and demographics of the region being studied. The direct damage module is used to evaluate the damage to the structural and non-structural building elements, transportation and lifeline components. The induced damage module evaluates damages due to fire following earthquake, hazardous materials release, inundation due to dam or levee failure and debris. Direct economic losses considered are the costs of structural and non-structural damage. Social losses evaluated include casualties and homelessness. Indirect economic losses include changes in employment, losses in tax revenue, losses in production and reduction in demand for production. The indirect loss module computes post-event demands and supplies and rebalances the economy by iteratively adjusting productions until the discrepancy between supplies and demands is within tolerable limits. However, unlike that done by Cho et al. (2000) and Gupta (2001), the network capacity constraints are not considered in the rebalancing process. Therefore, while HAZUS evaluates most of the losses in a comprehensive manner, the transportation-related losses considered are only those due to direct damage to the network; indirect losses resulting from commodity flow disruption and increased travel distances/times are not considered. The highly data-intensive nature of HAZUS also limits the analysis to a few counties at a time.

Gupta (2001) Gupta (2001) has developed a macroscopic methodology to eval-

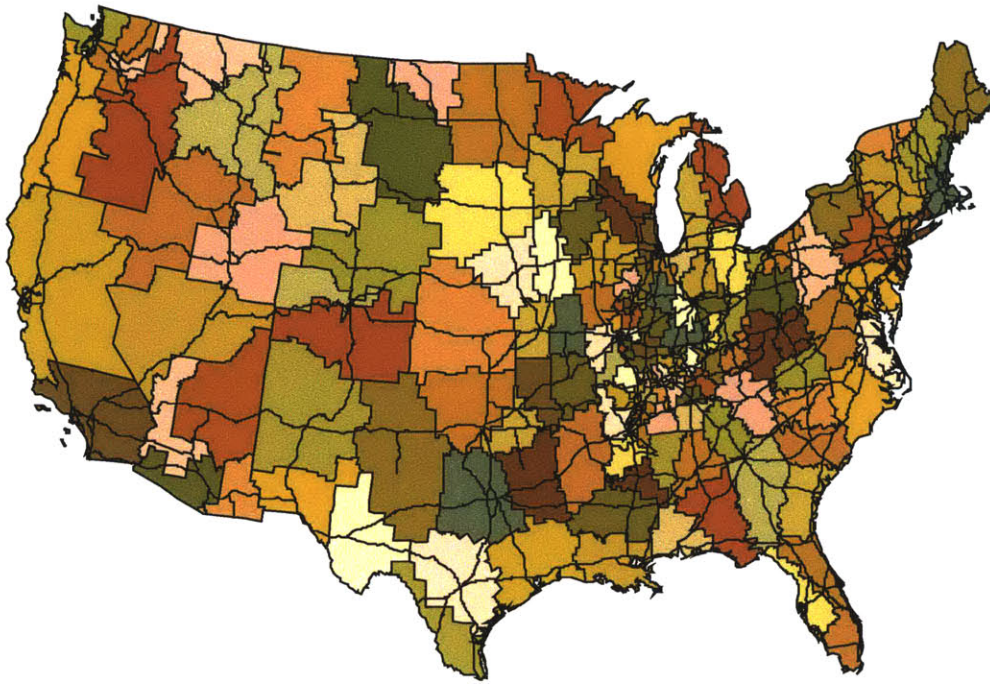


Figure 2-1: Analysis regions and transportation network (*Source:* Gupta (2001))

uate the economic and social losses at the national level. The methodology considers damage to the infrastructure, the resulting loss of functionality and the subsequent repair and recovery of functionality over time. Interactions among the economic sectors are accounted for by using an economic input-output model. Effect of damage to the lifelines and the residential sector on the economic sectors is included. Spatial interactions among regions are represented by commodity flows on the transportation network. The methodology therefore integrates attenuation, fragility, loss-of-function and recovery, network optimization and economic input-output models to estimate earthquake losses. The conterminous U.S is divided into a number of “analysis regions” around the nodes of the road network. The analysis regions are obtained by associating each county with the highway node that is closest to its centroid. The population, building inventory and economic activity of each analysis region are treated as being concentrated at its centroid. The transportation network includes all interstate highways, augmented by state highways near the epicenter.

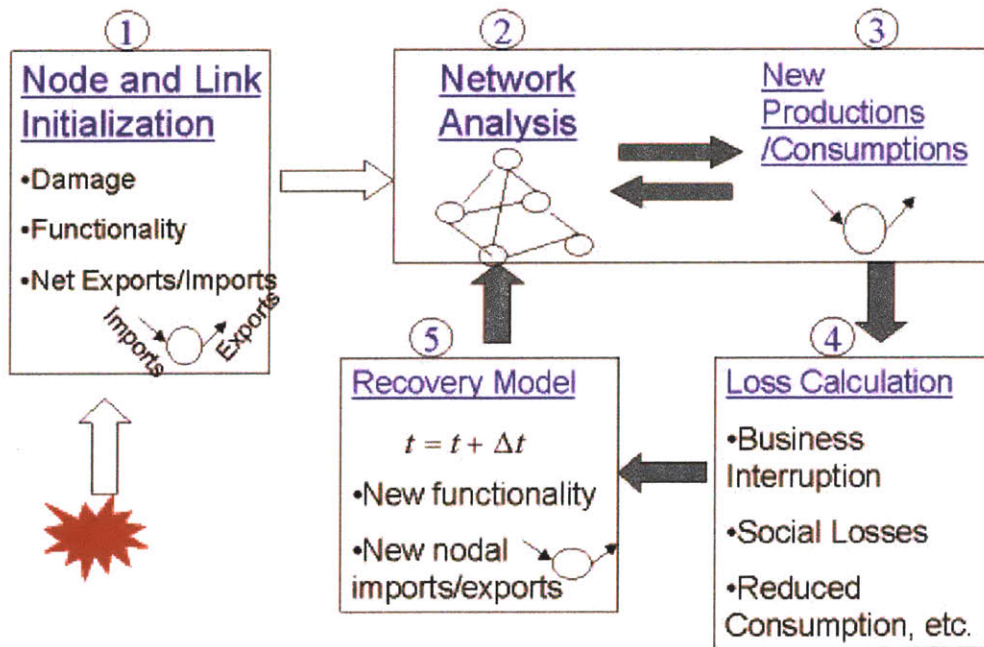


Figure 2-2: Loss estimation methodology

Figure 2-1 shows the analysis regions and the transportation network. There is a finer spatial discretization of the analysis regions and the network close to the epicenter, which progressively gets coarser at larger distances.

The logical flow of the methodology is shown in Figure 2-2. Time since the earthquake is discretized as $t_0 = 0^+, t_1, t_2, \dots$. At time t_0 , the local ground motion intensity is calculated at each analysis region and link and the state of damage of each infrastructure element is initialized. Damage-functionality relations are then used to calculate the initial functionality of the infrastructure elements. This includes buildings, bridges, highway pavements and “other lifelines”. The “other lifelines” category is a coarse representation of the essential lifelines in each region which include the transportation and utility lifelines. The productions of the economic sectors are calculated taking into account their reduced functionality. At each region, the net exports (imports if negative) are calculated as the difference between the net productions and the final consumptions. This concludes Step 1 of the procedure. Steps 2 and 3 are a sequence of node(region)-network iterations to determine the level of economic activity

that can be sustained at the region subject to network capacity constraints. For example, if a commodity cannot be shipped out of a region because of insufficient link capacity, then it will decrease its production of that commodity to meet the network constraint. Steps 2 and 3 are iteratively executed until the region's requirements are satisfied by the network. At convergence, the various indirect losses from the current time step are calculated (Step 4). In Step 5, time is increased from t_i to t_{i+1} and the functionality of the various infrastructure elements is updated using recovery relations. Steps 2-5 are repeated until all the elements have reached their pre-earthquake states.

The methodology of Gupta (2001) provides a more complete picture of the losses than the other methodologies discussed, since they are estimated from a global, system perspective. The earthquake effects on the national economy are considered as compared to the more microscopic analysis of Cho et al. (2000) and Werner et al. (2000). The seismic vulnerability of the economic sectors is considered unlike in Sohn et al. (2001a) and Werner et al. (2000), and a transportation network analysis is carried out unlike in HAZUS (2000). The recovery process for all the infrastructure elements is also explicitly modeled unlike in Sohn et al. (2001a) and Cho et al. (2000). This is useful in understanding the system dynamics as well as the evolution of losses over time.

The methodology also has some drawbacks compared to the other methodologies. The economic and transportation models are less sophisticated compared to those of Cho et al. (2000), Sohn et al. (2001a) and Werner et al. (2000). Network congestion, crosshauling of commodities and O-D flows (flow along paths) are not modeled. Instead a link-based formulation along with linear link costs is used. This is done for reasons of computational feasibility and solution time. The methodology is also less sophisticated compared to HAZUS in evaluating certain loss components such as social losses (casualties, homelessness) and induced losses (due to fire, flooding). There are other deficiencies such as:

- Certain classification systems in the methodology are rather coarse. For

example, bridges are classified as major or ordinary bridges depending on the span length. This does not adequately characterize differences in bridge fragilities based on construction material and superstructure type.

- There are errors in the loss estimates due to the spatial aggregation of regions and the sparseness of the network. For example, aggregating the building inventory and economic activity of the associated counties at the region's centroid can overestimate or underestimate the total losses depending on the actual spatial distribution of property. Similarly, leaving out the secondary roads in the network model can result in overestimating the transportation related losses as it overlooks the possibility of rerouting commodities around the damaged primary roads.
- The methodology is deterministic and does not include uncertainty. However, the loss estimates may be significantly affected by the uncertainties. For example, the loss of link functionality is underestimated by calculating bridge damage based on the mean fragility instead of the fragility simulated about the mean value. Similarly, ignoring the variability in building damage overestimates the loss of building functionality.
- The loss measures are rather aggregate - the methodology gives the direct and indirect losses at the national level, which may not accurately represent local losses. For example, while losses from a certain region or sector may be sensitive to a particular parameter/mitigation measure, they may be too small to show up in the aggregate loss estimates. Also, certain losses are not quantified, such as losses due to increased transportation costs.
- The methodology uses the macroseismic approach to compute the losses. As mentioned earlier, this is the more traditional approach. The methodology does not incorporate more recent advances in attenuation relations, site amplifications and fragility relations.

The literature review indicates that while there are earthquake loss methodologies that are highly advanced in modeling certain loss components, most do not model

the losses in a comprehensive, integrated manner. The macroscopic loss methodology of Gupta (2001) is one that includes the effects of infrastructure damage, loss of functionality, recovery of functionality over time, economic interactions and transportation network damage in evaluating the losses. However, this methodology also has certain deficiencies which have been discussed above.

In improving the methodology of Gupta (2001), this thesis completely addresses many of the above mentioned drawbacks, such as improving classification systems, refining the analysis regions and the network, developing disaggregate loss measures and incorporating recent advances in the field into the methodology. Other issues have been partially addressed - incorporation of uncertainty into certain model parameters, a coarse modeling of the network congestion by calibrating the link capacities and quantification of certain additional losses such as economic losses due to increased transportation costs and social losses due casualties. Issues that have not been addressed include modeling the crosshauling of commodities, OD flows and quantification of induced losses and other social losses due to homelessness etc.

Chapter 3 describes the revised methodology, which incorporates the above mentioned improvements.

Chapter 3

Methodology

This chapter discusses the improvements made in the methodology of Gupta (2001). For completeness, the entire revised methodology incorporating the improvements is described. This also helps in the better understanding of the results for scenario New Madrid earthquakes presented in Chapter 4

The spatial layout is first described. It basically consists of a number of “analysis” regions connected by a transportation network. The component models which further qualify the analysis regions and the transportation network are then described. Finally, the analytical framework which integrates the component models to evaluate the losses is explained.

While the methodology is universally applicable, the spatial layout, data and parameters are explained in the context of its application to the New Madrid scenario. There is significant uncertainty in all model data and parameters. The methodology does not comprehensively quantify or incorporate these uncertainties. Variability in damage alone is considered. While this is a very incomplete characterization, it provides a sense of the importance of uncertainty modeling. Further work on the methodology can attempt to comprehensively quantify and incorporate uncertainties into the model.

3.1 Representation of Spatially Varying Quantities and Transportation Network

This section describes the procedure for obtaining the analysis regions and the abstracted transportation network. The inventory data at the regions is also described.

The model is macroscopic and covers the entire conterminous U.S¹. The conterminous U.S is divided into a number of analysis regions, which are connected by the road transportation network. Each analysis region typically consists of a number of counties or in the epicentral region, census tracts. The nodes of the transportation network are the highway intersections, while the links are the highway segments connecting the nodes, along with the bridges on them.

Analysis Regions The analysis regions are obtained by aggregating the lowest geographical units considered (census tracts or counties), around the highway nodes. As can be observed in Figures 3-1 and 3-2, the metropolitan areas and counties with high population densities are concentrated close to the intersections of the National Interstate Highway System. Thus, it is a reasonable assumption to aggregate the counties around the highway nodes. However, only a subset of these nodes is considered for aggregating the counties. This is because there are several regions with a very high network density and using all the highway intersections for aggregating counties yields a non-uniform distribution of regions.

Each county is associated with the highway node closest to its centroid. All counties associated with the same highway node are aggregated to form an analysis region. Figure 3-3 shows the regions obtained by the above mentioned procedure and the counties comprising them. There is a finer spatial discretization in the New Madrid region for better accuracy in the geographical distribution of activities and facilities and in better accounting for local ground

¹Alaska and islands are ignored as they are not connected by the National Highway System. Further, they have negligible import/export associated with them.

motion amplification effects. Each analysis region has data regarding building inventory, population, economic activity and local soil conditions. The manner in which these data are obtained is described next.

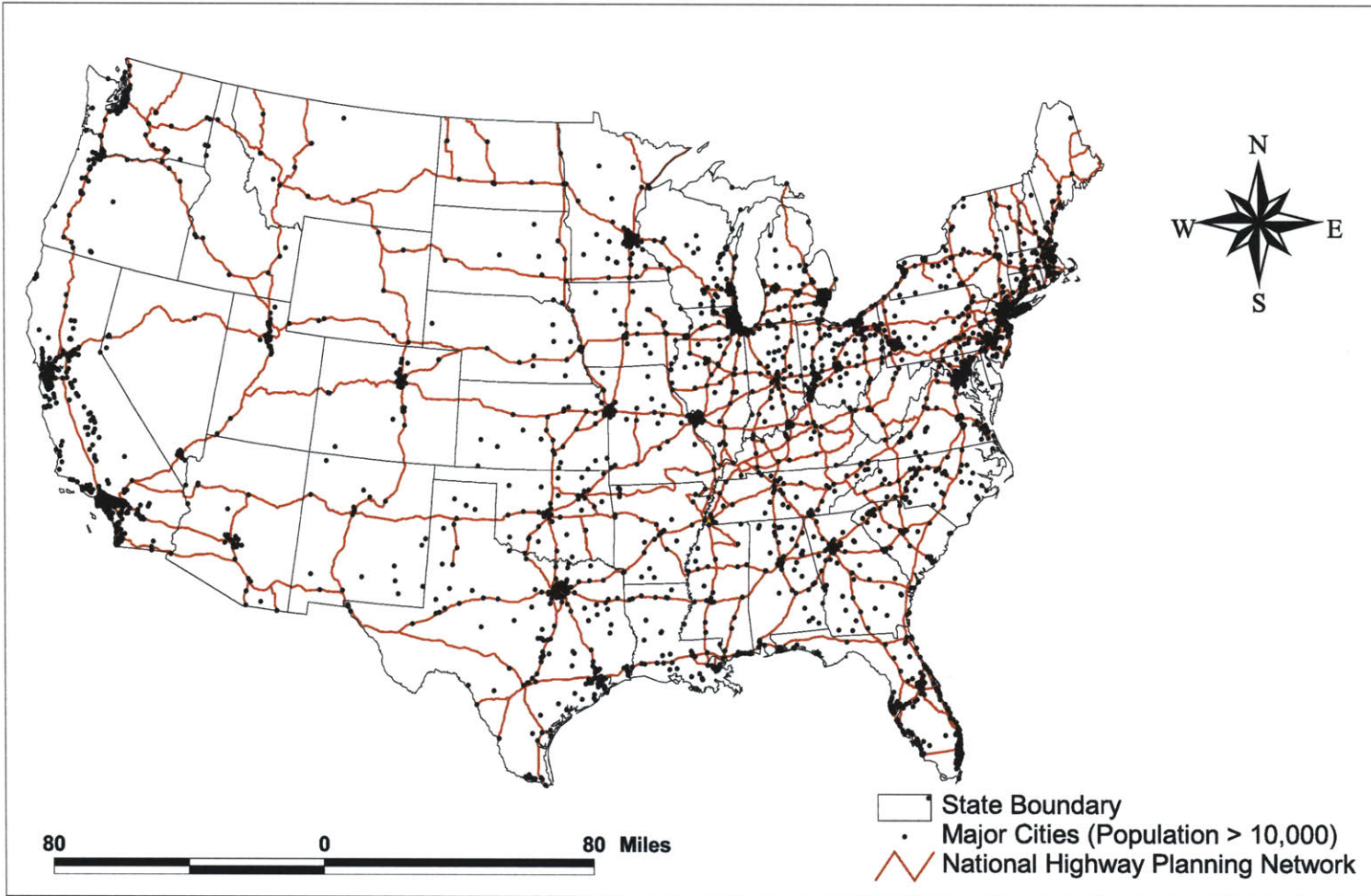


Figure 3-1: Distribution of Major Cities and Highways (*Source:* Gupta (2001))

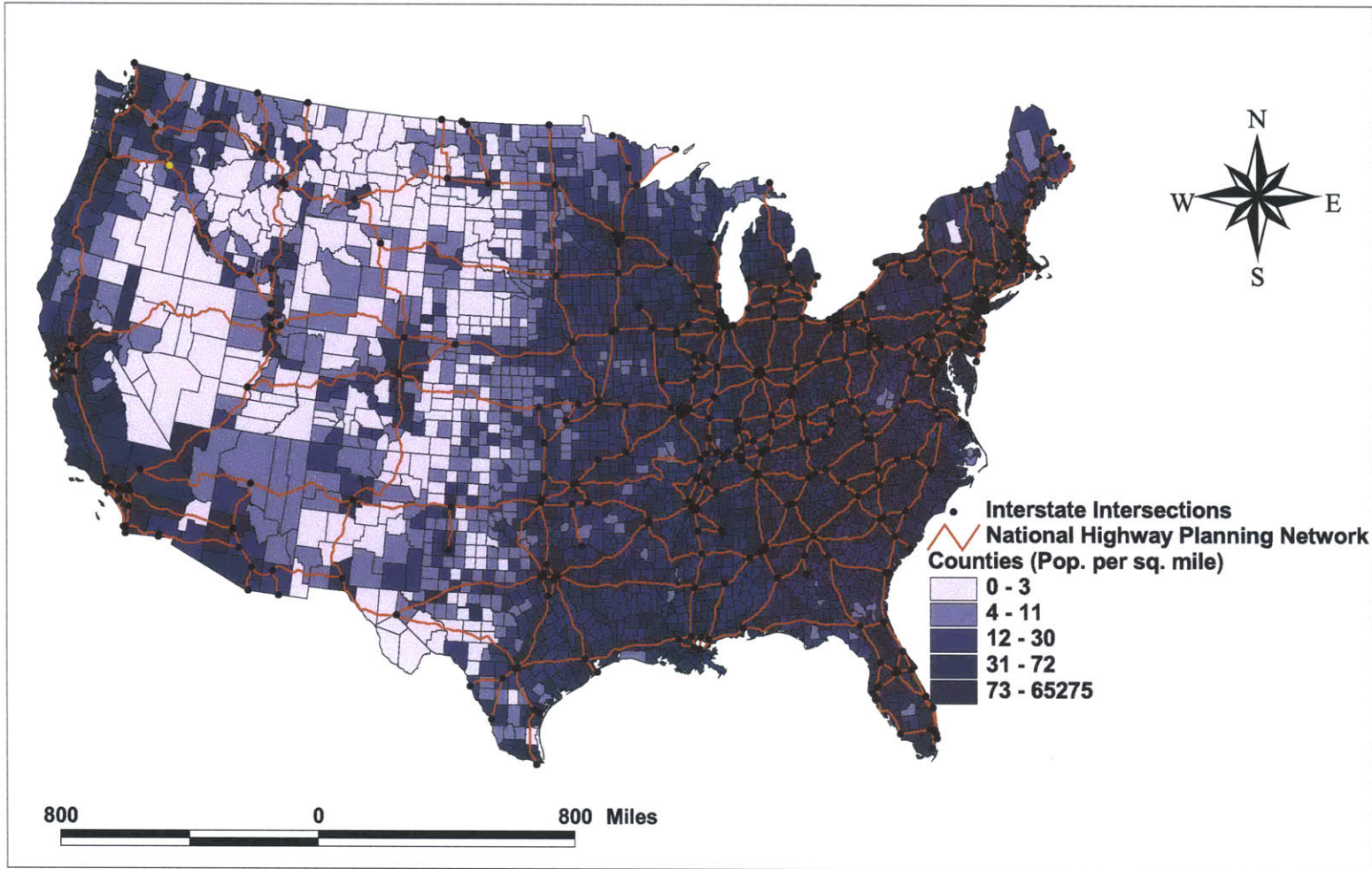


Figure 3-2: County population density and the National Highway System (*Source: Gupta (2001)*)

- **Building inventory:** The building inventory describes the floor areas of different building types in an analysis region. The building inventory at the county level is obtained from HAZUS (2000), which is aggregated to the analysis regions. HAZUS (2000) gives data regarding the floor areas of 28 occupancy classes, which are listed in Table 3.1. The present methodology uses a coarser classification with only 7 occupancy classes. The 7 classes are abstracted from ATC-13 (1985) and are considered to represent accurately enough distinct economic and occupancy sectors. This simplification is made for the sake of reducing memory and computation requirements. Table 3.2 describes the 7 occupancy classes. The floor areas of the 7 occupancy classes are obtained by aggregating the HAZUS (2000) data using the mapping in Table 3.3. For example, the residential inventory is obtained by aggregating the floor areas of HAZUS (2000) classes RES1-RES6.

The occupancy classification of a building determines its loss-of-functionality and recovery characteristics following the earthquake. However, the occupancy classification does not determine the seismic vulnerability of buildings. For example, a heavy industrial steel building would be damaged differently from an industrial masonry building. Therefore, the seismic vulnerability of a building is determined by its structural type. The methodology considers alternative structural classifications depending on the modeling approach - macroseismic or engineering (described in Chapter 2). The macroseismic approach considers 6 structural types (unreinforced and reinforced masonry, reinforced concrete, heavy and light steel and timber), which are taken to be broadly representative of the different structural types and their earthquake vulnerabilities. The engineering approach uses the 36 structural types from HAZUS (2000), which are given in Table 3.4 (L, M and H denote low-rise, mid-rise and high-rise, respectively). Although the HAZUS (2000) classification is very detailed, there is not much difference in the seismic vulnerability characteristics among some

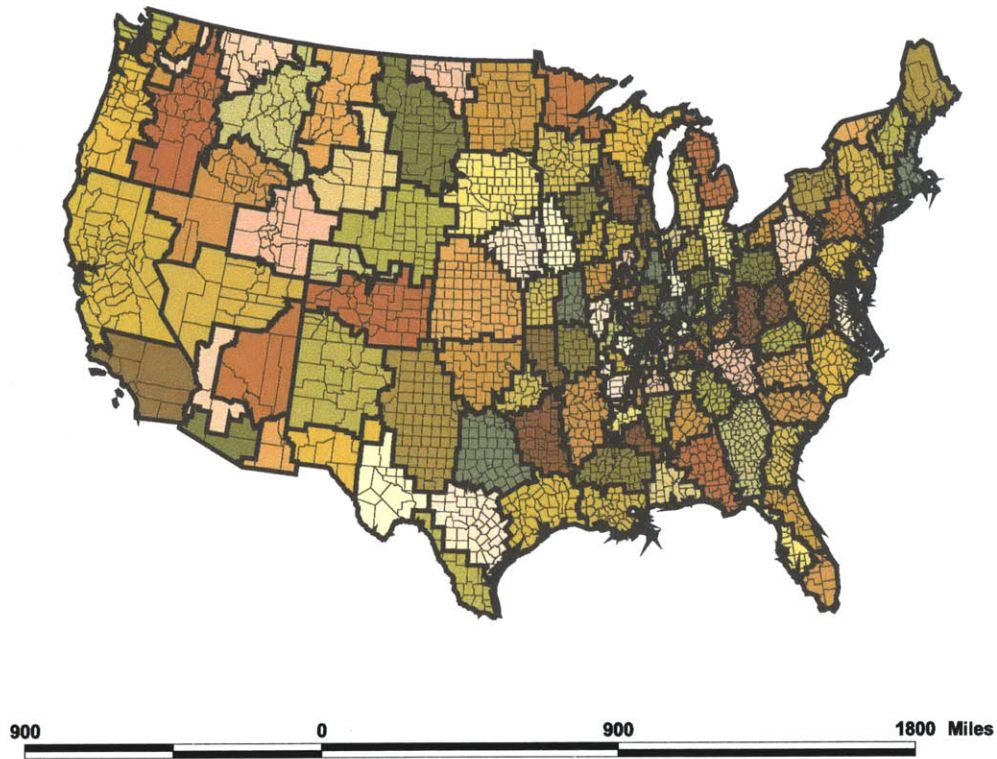


Figure 3-3: Aggregation of counties to form analysis regions (*Source:* Gupta (2001))

of its classes. For example, HAZUS (2000) gives very similar fragility characteristics for RM1L and RM2L. Therefore, even though the macroseismic structural classification is much coarser than the engineering one, it captures the major differences in the seismic vulnerability characteristics across building types.

Each occupancy class includes buildings of different structural types. Damage to an occupancy class is calculated as the weighted average of the damages to the structural types making up that occupancy class. The distribution of the structural types within each occupancy class is obtained from HAZUS (2000). HAZUS (2000) gives the distribution of the 36 structural types within each of its 28 occupancy classes. The corresponding values for the occupancy and structural classes used in this methodology are obtained by mapping them to the HAZUS (2000) classes; see Table 3.3. In the macroseismic approach the structural classes are different from

those of HAZUS (2000). In that case, a structural class mapping is also defined, which is given in Table 3.5.

- **Contents Inventory:** In the absence of data on the contents of each occupancy class, the contents inventory is assumed to be 75% of the corresponding building inventory. This assumption is based on a survey of literature including ATC-13 (1985) and HAZUS (2000).
- **Economic data:** The economic data includes the productions and domestic consumptions of various economic sectors in each region. We consider 13 economic sectors (from Okuyama et al. (1999)), which are listed in Table 3.6. This classification system is used as it represents the national economy and commodity flows at a reasonable level of detail and is consistent with the available economic data. The productions and domestic consumptions at the national level are obtained from Sohn et al. (2001a). The manner in which they are disaggregated to the analysis regions is described later in this chapter, after introducing the economic input-output model.

In order to model the reduced production levels of the economic sectors due to earthquake damage, the sectors are mapped into the occupancy classes, as shown in Table 3.7. The functionality of an economic sector is taken to be that of the occupancy class to which it is mapped. For example, the primary metals industry, which is one of the 13 economic sectors, is a heavy industry. Its functionality level is therefore the same as that of the heavy industry occupancy class within the analysis region where the activity is located. Certain economic sectors (agriculture, mining, and construction) are not mapped to any occupancy class. These sectors are considered “invulnerable” to earthquakes and consequently do not suffer any loss of functionality.

- **Population:** The population of each analysis region is the aggregate of the population of the associated units (counties, census tracts). The latter is obtained from the 1990 U.S. Census of Population and Housing.

Label	Occupancy Class
RES1	Single Family Dwelling
RES2	Mobile Home
RES3	Multi Family Dwelling
RES4	Temporary Lodging
RES5	Institutional Dormitory
RES6	Nursing Home
COM1	Retail Trade
COM2	Wholesale Trade
COM3	Personal and Repair Services
COM4	Professional/Technical Services
COM5	Banks/Financial Institutions
COM6	Hospital
COM7	Medical Office/Clinic
COM8	Entertainment & Recreation
COM9	Theaters
COM10	Parking
IND1	Heavy
IND2	Light
IND3	Food/Drugs/Chemicals
IND4	Metals/Minerals Processing
IND5	High Technology
IND6	Construction
AGR	Agriculture
REL	Church
GOV1	General Services
GOV2	Emergency Response
ED1	Schools
ED2	Colleges/Universities

Table 3.1: HAZUS building occupancy classes (*Source:* HAZUS (2000))

No.	Occupancy Class	Description
1	Residential	Permanent, temporary and group institutional housing
2	Commercial	Wholesale and retail trade, services etc.
3	Heavy Industry	Paper mills, steel plants, automobile plants, etc.
4	Light Industry	Textiles, office equipment, electrical equipment, etc.
5	High Technology	Semi-conductor and computing equipment manufacturing
6	Food & Drug	Food manufacturing plants, cooking oils, beverage plants, etc.
7	Chemical	Fertilizers, food chemicals, plastics, rubber, soaps, etc.

Table 3.2: Building occupancy classes used in the methodology

Occupancy Class in Model	HAZUS Occupancy Classes
Residential	RES1 - RES6
Commercial	COM1-COM10, GOV1, GOV2
Heavy Industry	IND1, IND4
Light Industry	IND2
High Technology	IND5
Food & Drug	IND3
Chemical	IND3

Table 3.3: Mapping of the occupancy classes used in the methodology to the HAZUS classification

- **Local geologic conditions:** Local geologic information is needed to assess local ground motion amplification effects (in the engineering approach). For the New Madrid region, this information is obtained from Toro and Silva (2001); see Figure 3-4. Toro and Silva (2001) classify local conditions into 6 classes depending on near surface soil type. They also suggest a rough correspondence between their soil classes and the more commonly used NEHRP Uniform Building Code (1997) soil classes. Table 3.8 lists the Toro and Silva (2001) classification and its mapping to the NEHRP classes. Outside the New Madrid region, hard rock site conditions are assumed. This does not affect the analysis very much, since there is no significant damage in those regions.

The building inventory, population, economic activity and soil conditions are treated as being concentrated at the population centroid of the analysis region. The population centroid of an analysis region is the weighted average of the geometric centroids of the counties comprising that region, using weights proportional to population. This is an improvement in the methodology of Gupta (2001), where the geometric centroids are used. Figure 3-5 compares the population and geometric centroids for certain analysis regions. The two centroids differ considerably in some cases, indicating a non-uniform spatial distribution of population in the counties.

Transportation network: The road transportation network includes all the inter-

No.	Label	Description
1	W1	Wood Light Frame
2	W2	Wood, Commercial and Industrial
3	S1L	Steel Moment Frame
4	S1M	
5	S1H	
6	S2L	Steel Braced Frame
7	S2M	
8	S2H	
9	S3	Steel Light Frame
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls
11	S4M	
12	S4H	
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls
14	S5M	
15	S5H	
16	C1L	Concrete Moment Frame
17	C1M	
18	C1H	
19	C2L	Concrete Shear Walls
20	C2M	
21	C2H	
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls
23	C3M	
24	C3H	
25	PC1	Precast Concrete Tilt-Up Walls
26	PC2L	Precast Concrete Frames with Concrete Shear Walls
27	PC2M	
28	PC2H	
29	RM1L	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms
30	RM1M	
31	RM2L	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms
32	RM2M	
33	RM2H	
34	URML	Unreinforced Masonry Bearing Walls
35	URMM	
36	MH	Mobile Homes

Table 3.4: HAZUS structural classes (*Source:* HAZUS (2000))

Structural Class in Model	HAZUS Structural Classes
Unreinforced masonry	URML
Reinforced masonry	RM1L, RM2L
Reinforced concrete	C1L, C3L, PC2L
Heavy steel	S1L, S2L, S4L, S5L
Light steel	S3
Timber	W1, W2

Table 3.5: Mapping of the macroseismic structural classes to the HAZUS structural classes

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 3.6: Economic sector classification (*Source:* Okuyama et al. (1999))

Economic Sector	Occupancy Class
Agriculture, forestry and fisheries	-none-
Mining	-none-
Construction	-none-
Food and kindred products	Food & Drug
Chemicals and allied products	Chemical
Primary metals industries	Heavy Industry
Fabricated metal products	Heavy Industry
Industrial machinery and equipment	Heavy Industry
Electronic and electric equipment	High Technology
Transportation equipment	Heavy Industry
Other non-durable manufacturing	Light Industry
Other durable manufacturing	Light Industry
Commercial, services and government enterprises	Commercial

Table 3.7: Mapping of the economic sectors to the occupancy classes

Toro-Silva Classification	NEHRP Classification
Embayment Lowlands	Stiff soil (D)
Embayment Uplands	Stiff soil (D)
Ozarks Uplands	Stiff soil (D)
Crowley's Ridge	Stiff soil (D)
Glacial Till	Very dense soil and soft rock (C)
Ozarks Rock	Hard rock (A)

Table 3.8: Mapping of the Toro-Silva soil classes to the NEHRP classes

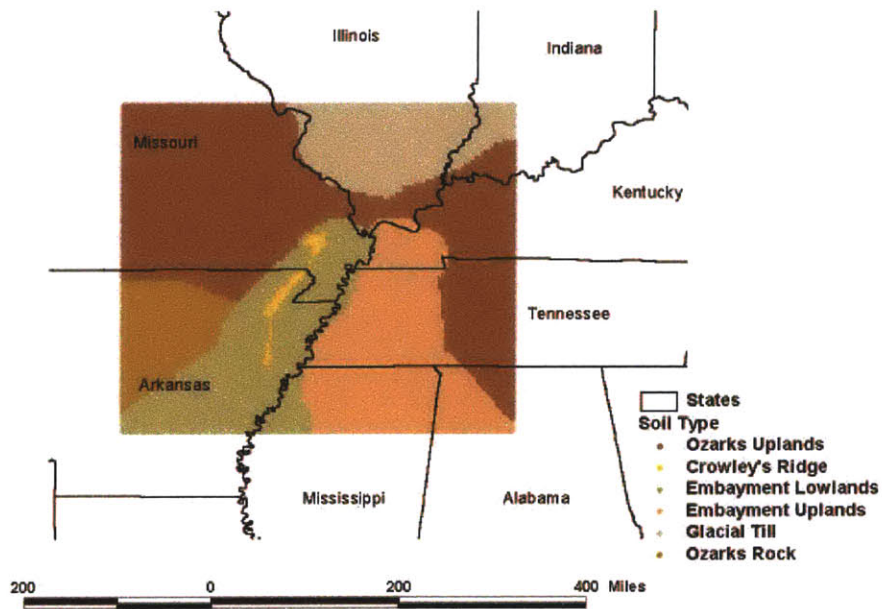


Figure 3-4: Soil map of the New Madrid region (*Source:* Toro and Silva (2001))

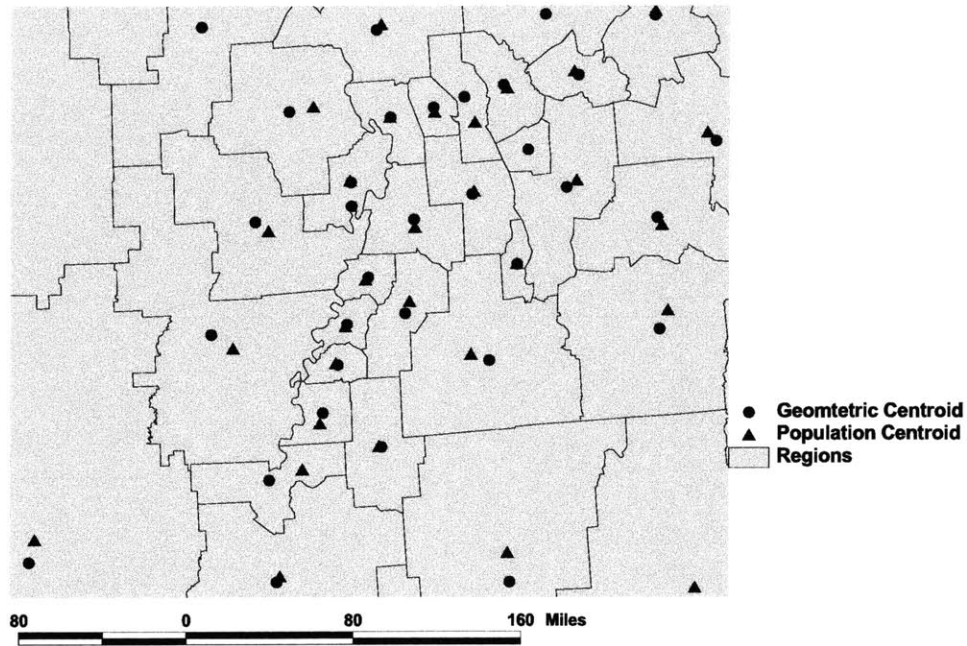


Figure 3-5: Locations of the geometric and population centroids

state highways. In the New Madrid region, the network is densified by including some state highways. The interstate and state highways are extracted from the National Transportation Atlas Database (NTAD) (Bureau of Transportation Statistics (2000)). The link data includes length, capacity and start and end nodes. Soil conditions along the links are not considered, primarily due to the extensive computations required to account for the continuous variation of soil conditions along the links. Hard rock conditions are assumed instead. Figure 3-6 shows the network used in the New Madrid scenarios.

Bridges along the highway segments are modeled only in the New Madrid region (within a radius of about 160km from the epicenter), where there is the possibility of highway closures due to bridge damage. The bridges are extracted from the National Bridge Inventory (NBI) system (Federal Highway Administration (FHWA) (1995)) and are assigned to the closest highway segment. NBI gives the structural and traffic characteristics of each bridge. In addition, the site conditions at the bridge are evaluated from the Toro and Silva (2001) soil

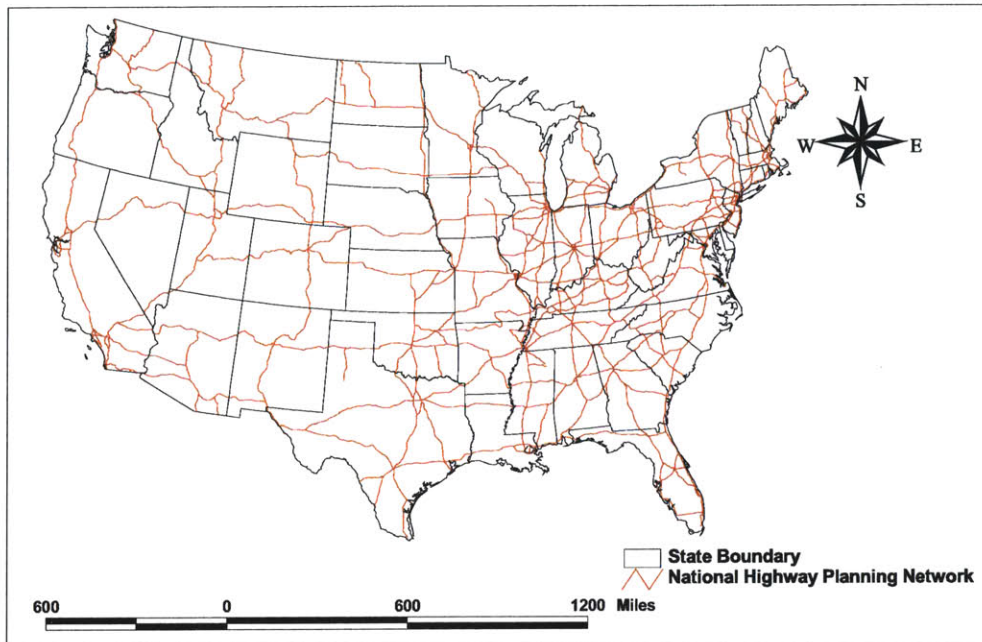


Figure 3-6: Highway network used in the scenario analysis(*Source: Gupta (2001)*)

map. Figure 3-7 shows the bridges in the New Madrid region overlaid onto the highway network.

Having obtained the analysis regions and the transportation network by the procedures described above, the analysis regions are then connected to the network by associating each region with the highway node closest to its centroid. In the determination of the highway flows, the net exports and imports of the commodities at the highway nodes are taken to be those of the analysis regions associated with it. The number of regions, highway nodes, links and bridges depend on the discretization of the analysis regions and the resolution of the network. For the resolution adopted in Gupta (2001), the model has 152 analysis regions, 484 highway intersections, 1448 links and 1958 bridges. The effects of increasing the model resolution by considering a finer spatial discretization of the analysis regions and a more detailed network are examined in Chapter 4.

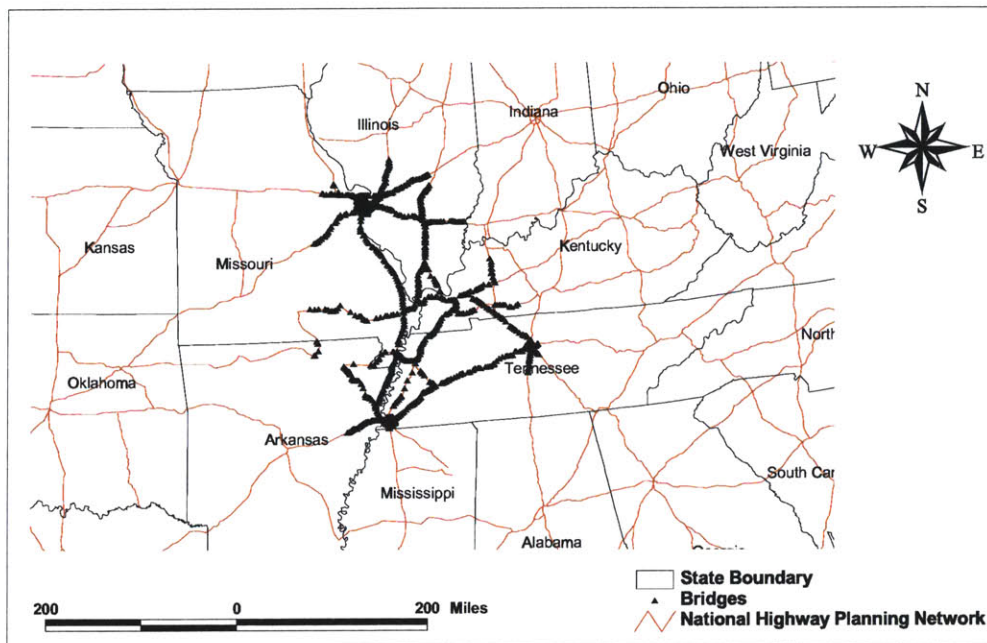


Figure 3-7: Highway bridges used in the scenario analysis (*Source: Gupta (2001)*)

3.2 Component Models

The loss evaluation methodology integrates 5 basic component models, namely the attenuation, fragility, loss-of-function and recovery, economic input-output and network analysis models. For each component, a general description of the model is first given. Data and model parameter selections for application to New Madrid scenario earthquakes are given next. For some component models, such as the attenuation and fragility models, there are alternate formulations, namely the macroseismic and engineering approaches. The parameters in Gupta (2001) are set according to the macroseismic approach. The revised methodology incorporates the engineering approach as well. Results vary significantly with the modeling approach (Chapter 4).

1. **Attenuation Model:** The attenuation model is used to calculate the intensity of ground motion at the centroids of the analysis regions and along the transportation links.

Data and Parameters:

- The macroseismic approach uses the attenuation relation of Bollinger (1977),

which gives the ground motion intensity in terms of the Modified Mercalli Intensity (MMI). The intensity obtained from the Bollinger (1977) attenuation relation is taken to be that for an “average” site in the New Madrid region. Hence, the intensity is not multiplied by site amplification factors.

- The attenuation function of Toro and Silva (2001) is used in the engineering approach. In this case, the ground motion intensity is characterized in terms of peak ground acceleration (PGA), spectral acceleration (Sa) and peak ground velocity (PGV) at a hard rock site. The actual intensity at the site is obtained by multiplying the hard rock intensity by soil amplification factors depending on the local soil conditions. The soil amplification factors used are from Dobry et al. (2000).

2. Fragility Model: The fragility model is used to assess the state of damage of various infrastructure elements (buildings, bridges etc.). A measure of the infrastructure damage is the damage ratio, which is defined as the ratio of the dollar loss to a structure to its replacement value. The damage ratio varies from 0 (no damage) to 1 (collapse or complete damage). Fragility curves give the damage ratio as a function of some ground motion intensity parameter for different seismic vulnerability classes.

Uncertainty in damage: There is variability in damage from element to element within an infrastructure class because of differences in structural design, construction, age etc. Consequently, the fragility curve itself is a random function with random parameters. Quantifying all these uncertainties is difficult. In order to make the analysis more tractable, typically many simplifying assumptions are made. For example, the uncertainty is incorporated into a single parameter of the fragility curve, assuming that the functional form and other parameters are deterministic.

Fragility curves used in the methodology have the cumulative distribution function (cdf) of the normal or the lognormal distributions. The fragility parameters are therefore the mean and standard deviation (log mean and log standard devi-

ation) of the distributions. The uncertainty in damage is incorporated into the mean of the cdf, μ . It is considered to be a random variable with a probability density function (pdf) $f_\mu(x)$ and mean $\bar{\mu}$. $\bar{\mu}$ represents the average fragility of an infrastructure class, such as unreinforced masonry buildings or single span steel bridges. $f_\mu(x)$ represents the variation in the fragility within elements of the same class. For example, while unreinforced masonry buildings have an average fragility, there will be buildings with fragilities higher or lower than the average, resulting in the variability in damage from building to building for the same intensity of ground motion. The consideration of the variability in damage in the infrastructure elements is an improvement in the methodology of Gupta (2001), where damage is calculated deterministically.

The manner in which the uncertainty in fragility is used in the damage calculation depends on the infrastructure element considered. To illustrate this, the damage calculation for buildings and bridges is described. In the case of buildings, damage is evaluated for a *group(population)* of buildings. The average damage is obtained by considering the variation in fragility across the population and is given by:

$$E(D) = \int_{-\infty}^{\infty} \phi(I, x) f_\mu(x) dx \quad (3.1)$$

where:

$E(D)$ is the average damage ratio

$\phi(I, x)$ is the fragility relation which gives the damage ratio as a function of the intensity I and the fragility x

$f_\mu(x) dx$ is the expected fraction of buildings with fragility x

In case of bridges, damage is calculated for an *individual* bridge, and not for a group as in buildings. The fragility of an individual bridge is simulated to model the variability in damage from bridge to bridge.

It is to be noted that the consideration of the uncertainty in damage does not significantly change the direct loss estimates compared to when the damages are obtained deterministically. Intuitively, this is because the damages average out,

Damage State	Damage Ratio%
None	0
Slight	0.005
Light	0.05
Moderate	20
Heavy	45
Major	80
Complete	100

Table 3.9: ATC-13 (1985) building damage states

i.e., there will roughly be an equal number of elements with fragilities above and below the mean fragility. However, the loss-of-functionality and the indirect loss estimates are substantially affected by the consideration of uncertainty. This is fully discussed later in the chapter.

Data and Parameters:

- The infrastructure elements considered in the methodology are buildings and their contents, bridges, pavements and lifelines.
- ATC-13 (1985) is the primary source for the fragility curves used in the macroseismic approach. The ATC-13 (1985) fragilities are based on expert opinion and use MMI as the intensity unit. ATC-13 (1985) considers 7 damage states and provides the probability of a structure being in each state for intensities ranging from 6-12MMI. Table 3.9 lists the damage states and the corresponding damage ratios. The expected damage for a each intensity level is calculated from the damage ratios and the corresponding probabilities. A functional fragility relation is assumed, in the form of a normal cumulative distribution function (cdf) and its parameters are obtained from a least squares fit to the ATC-13 (1985) expected damages. Figure 3-8 illustrates such a fit for pavements.
- The fragility curves in the engineering approach are from HAZUS (2000). HAZUS (2000) derives the fragility curves from an engineering analysis. The fragilities are in terms of peak ground acceleration (PGA) for lifelines, spectral acceleration (Sa) for bridges, spectral displacement (Sd) for build-

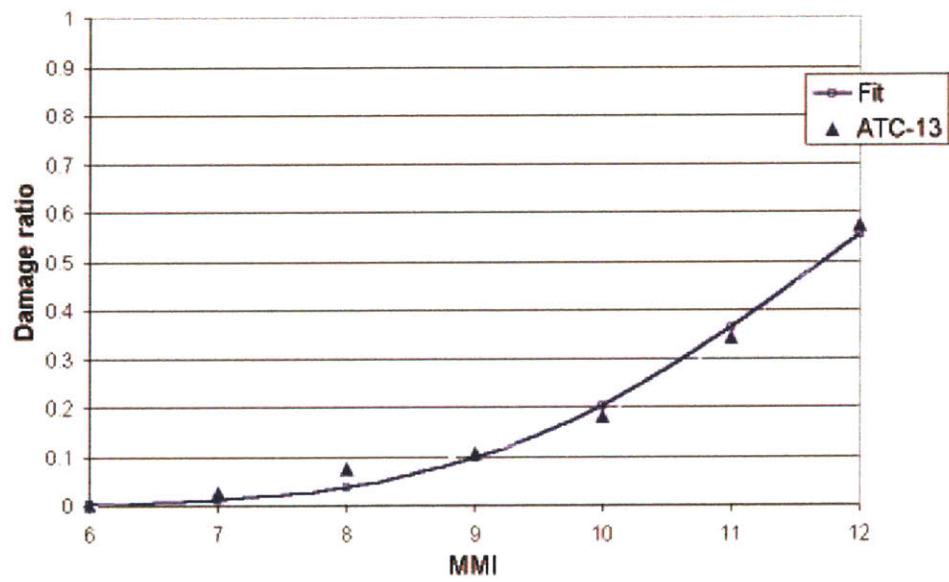


Figure 3-8: Estimation of fragility parameters of pavements from ATC-13 (1985) data

ings and permanent ground displacement (PGD) for pavements. HAZUS (2000) gives the fragilities in the form of lognormal cdf curves.

- The infrastructure fragility parameter μ which incorporates the uncertainty in damage is taken to be normally distributed in the macroseismic approach and lognormally distributed in the engineering approach. The parameters of the distributions are derived by Jammalamadaka (2002b) from ATC-13 (1985) and HAZUS (2000) data respectively.
- Buildings: Building fragilities are based on the structural system. The fragility parameters of the 6 structural types (unreinforced and reinforced masonry, reinforced concrete, heavy and light steel and timber) considered in the macroseismic approach are obtained from fits to the ATC-13 (1985) data. The fragilities of the 36 building classes considered in the engineering approach are from HAZUS (2000). While ATC-13 (1985) gives a single fragility curve for buildings, HAZUS (2000) gives separate fragility curves for structural, non-structural drift sensitive and non-structural acceleration sensitive building components. The structural components typically have higher fragilities than the non-structural components.
- Contents: Contents fragilities in the macroseismic approach are based on occupancy type and are derived for the 7 occupancy classes listed in Table 3.2. Contents fragilities in the engineering approach are from HAZUS (2000). HAZUS (2000) considers acceleration sensitive non-structural damage as a good indicator of contents damage and assigns the same fragilities to all contents.
- Pavements: Pavement fragility is from ATC-13 (1985). The fragility is that of a section of the highway. The HAZUS (2000) fragilities are in terms of permanent ground displacement (PGD). Estimation of the PGD requires data on ground failure (liquefaction, landslides etc.) which is not available at this time. Therefore, the ATC-13 (1985) fragilities are used in the engineering approach also. In order to use the ATC-13 (1985)

fragilities in the engineering approach, the intensity in PGA is converted to MMI using the formula of Trifunac (1976) ($MMI = 10.5 + 1.48\ln(PGA)$).

- Bridges: The ATC-13 (1985) bridge classification is very coarse and is not used. The HAZUS (2000) classification and fragilities are used instead in both the macroseismic and engineering approaches. HAZUS (2000) classifies bridges into 28 types based on the year built, number of spans, length of span and construction material and gives the fragilities in terms of S_a (1sec). In order to use the HAZUS (2000) fragilities in the macroseismic approach, the intensity in MMI is converted to PGA using the conversion of Bernreuter (1981):

$$\ln(PGA) = 1.79 + 0.75I - 0.323\ln(R) \quad (3.2)$$

where:

PGA is in cm/s^2

I is the intensity in MMI

R is the epicentral distance in km

The PGA obtained is converted to S_a (1sec) using the formula of Newmark and Hall (1976) ($S_a(1sec) = 0.5*PGA$).

Alternative bridge classification systems and fragilities are available, namely those of Hwang et al. (1998) and DesRoches et al. (2002). Hwang et al. (1998) and DesRoches et al. (2002) have developed fragility curves specifically for bridges in Mid-America. Sensitivity of the results to the alternative bridge classification systems and fragilities is examined in Chapter 4.

- Lifelines: The lifelines category is a very coarse representation of the essential lifelines in a region. The electricity-power distribution network (transmission towers) and the transportation system (city streets) within the analysis regions are the lifelines considered in the methodology. Fragilities of transmission towers and city streets are each obtained from ATC-13 (1985) and HAZUS (2000). These fragilities consider the damage to an

individual component of the system. The methodology considers the damage to these components to be a very rough estimate of the damage to the intra-regional electricity and transportation lifeline systems. System and network effects of lifeline damage are not modeled.

3. Loss-of-function and Recovery Models:

Loss-of-function model: Loss-of-function relations give the initial functionality based on the damage ratio D , i.e., $F(0) = c(D)$, where $F(0)$ is the functionality immediately following the earthquake ($0 \leq F(0) \leq 1$) and $c(D)$ is some function, the exact form of which is given later in this section.

Effect of variability in damage on the loss-of-function calculation: Considering the variability in damage from facility to facility significantly affects the initial average functionality estimates. This is illustrated below for buildings and bridges. In the case of buildings, the initial functionality considering the variability in damage is obtained as:

$$F(0) = \int_{-\infty}^{\infty} c[D(x)]f_{\mu}(x)dx \quad (3.3)$$

where:

$D(x)$ is the damage to buildings with fragility parameter x at a given location
 $c[D(x)]$ is the corresponding initial functionality

In Equation 3.3, the initial functionality is found as an average of the functionalities of buildings suffering different damage levels. Calculation of the initial functionality in a deterministic manner, based on the average damage $E(D)$ (Equation 3.1) is incorrect and overestimates the loss of functionality. For an illustration, we consider residential buildings. Figure 3-9 shows the damage-functionality relationship for such buildings, which is highly non-linear. For a damage ratio less than 4%, there is no loss of functionality. There is a rapid decrease of functionality beyond that and for a damage ratio $\geq 6\%$, a residen-

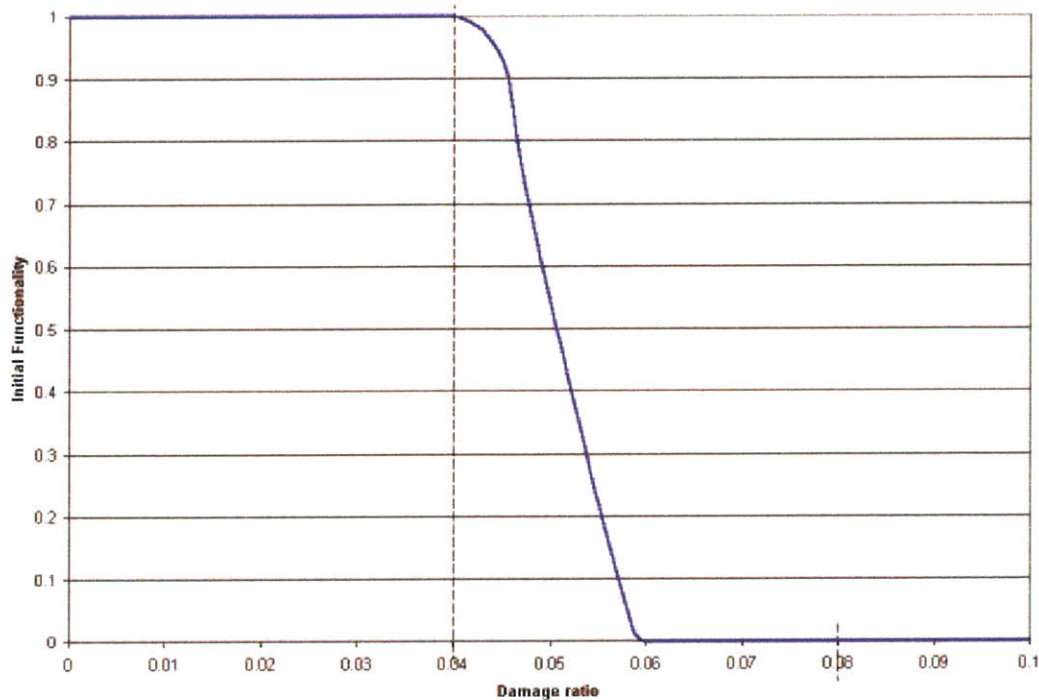


Figure 3-9: Damage-functionality relation for residential buildings

tial building has no initial functionality². Consider two residential buildings, one of which suffers 4% damage and the other 8% damage. Calculating the functionality based on the average damage (6%), gives an average initial functionality of 0% which is incorrect because of the non-linearity. Considering the variability in damage, finding the initial functionality for variable damage levels, and then taking the average gives an initial functionality of 50% $(0 + 100/2)$. Thus, the loss of functionality may be significantly overestimated by ignoring the variability in damage across buildings.

In the case of bridges, ignoring the variability in damage has the opposite effect of underestimating the loss of link functionality. This is because a link is a series system with pavement segments and bridges as elements. The link functionality is therefore determined by the minimum of the bridge and pavement functional-

²Although the initial functionality decreases very rapidly from 4-6% damage, the loss-of-functionality is only for a very short time at 6% damage, typically for a couple of days

ities. Simulating the fragilities results in some elements with fragilities greater than the mean fragility. These are damaged more and have lower functionalities compared to the case when the average fragilities are considered. Since it is the minimum element functionality that determines the overall link functionality, there is a greater loss of functionality when the fragilities are considered as stochastic as compared to the deterministic case.

Recovery Model: The recovery model describes the recovery of functionality of the infrastructure elements post-earthquake, including interaction effects. The functionality of a facility, such as a commercial building or a factory, at any time t following the earthquake is based on its own level of damage and the functionality of other components with which it interacts. The functionality of facility i based exclusively on its own level of damage is referred to here as its “physical” functionality $F^{i,phy}(t)$, $0 \leq F^{i,phy}(t) \leq 1$. This is its maximum possible functionality. The “actual” functionality of the facility depends on the functionality of other components and may be lower than this maximum possible value. For example, if the electricity distribution system in the region is not functioning, then a factory that depends on electricity for operation will not be able to function as well. Interactions also affect the rate of recovery. For example, if the roads leading to a facility are damaged, it will be difficult to access the facility and hence its reconstruction rate will be slowed down. The effect of interactions in reducing the functionality as well as the recovery rate below the maximum³ values is represented by the following equations:

$$F^{i,act}(t) = F^{i,phy}(t) * RF_1 \quad (3.4)$$

$$\frac{dF^{i,phy}(t)}{dt} = \frac{dF^{i,phy}(t)}{dt} \Big|_{max, F^{i,phy}(t)} * RF_2 \quad (3.5)$$

where:

³based on “normal” non-emergency schedules

$\left. \frac{dF^{i,phy}(t)}{dt} \right|_{max, F^{i,phy}(t)}$ is the maximum possible rate of recovery when the physical functionality is $F^{i,phy}(t)$

$\frac{dF^{i,phy}(t)}{dt}$ is the recovery rate of physical functionality accounting for interaction effects

RF_1 and RF_2 are factors which reduce the functionality and the recovery rate of a facility below the maximum values due to interactions with other components. The functional form of the factors depends on the interaction model - additive or multiplicative model. The alternative interaction models are discussed shortly.

Figure 3-10 illustrates the effects of interactions on the functionality and the recovery rate. Recovery Curve 1 shows the recovery of functionality of an element over time without any interactions. For example, this could depict the rebuilding of a factory when all other sectors are fully functional. However, the repair process could be slowed down because of accessibility problems or unavailability of labor. Recovery Curve 2 shows the recovery of functionality when it is rebuilt at a slower rate because of interaction effects (Equation 3.5). Finally, even though the factory may be repaired to a certain extent and has the capability of producing goods, it may not be able to actually do so if there is no power supply. Therefore, the actual functionality of the factory may be lower than its physical functionality because of interaction effects (Equation 3.4). Recovery Curve 3 represents this.

Interaction models: Two interaction models are considered namely the additive model and the multiplicative model.

- Additive model: In this model, the reductions in the functionality and the recovery rate of a facility is taken to be the weighted average of the lack of functionality of the other components on which the given facility depends.

The reduction factors are given by:

$$RF_1 = 1 - \frac{\sum_j \gamma_{ji,add}(1 - F^{j,phy}(t))}{n_1} \quad (3.6)$$

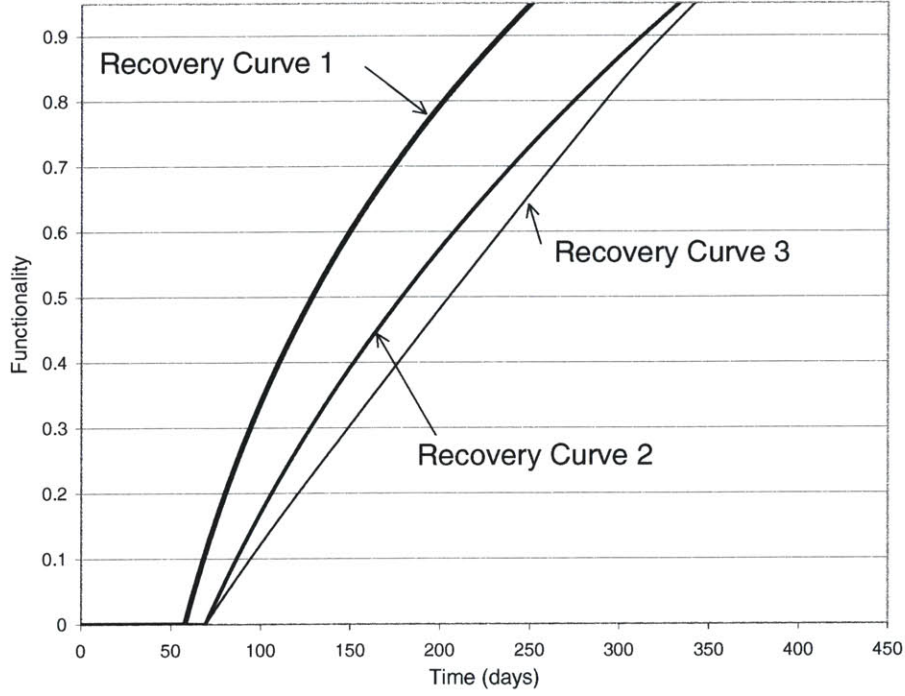


Figure 3-10: Hypothetical recovery curves *Source:* Gupta (2001)

$$RF_2 = 1 - \frac{\sum_j \beta_{ji,add}(1 - F^{j,phy}(t))}{n_2} \quad (3.7)$$

where:

$\gamma_{ji,add}$ is an interaction coefficient which controls the effect of functionality of component j on that of i

n_1 is the number of components which affect the functionality of i

$\beta_{ji,add}$ is an interaction coefficient which controls of the effect of functionality of j on the recovery rate of i

n_2 is the number of components which affect the recovery rate of i

Larger values of $\gamma_{ji,add}$ and $\beta_{ji,add}$ imply greater dependence of i on j , i.e., there is greater reduction in the functionality and recovery rate of i due to the lack of functionality of j .

Deficiency in the additive model: The additive model may not represent some interactions properly, as a result of the averaging of the lack of

functionalities of the interacting components. To illustrate this, consider a facility i which is initially considered to depend on a single component j_1 , with $\gamma_{1,add} = 1$. If the functionality of j_1 is 0, then the functionality of i also goes to 0 as $RF_1 = 1 - \frac{\gamma_{1,add}(1-F^{j_1,phy}(t))}{1} = 1 - \frac{1(1-0)}{1} = 0$. Now, consider i also to depend on another facility j_2 with $\gamma_{2,add} = 0.1$ (which implies a low importance of j_2 on i) and $F^{j_2,phy}(t) = 1$, i.e., j_2 is fully functional. The functionality of i now does not become 0, but is only halved since $RF_1 = 1 - \frac{1(1-0)+0.1(1-1)}{2} = 0.5$. Therefore, the effect of j_1 on i decreases by considering i to weakly depend on another component j_2 . The additive model is therefore not logically correct as the interaction effects may decrease by simply considering a facility to depend on a larger number of components. This motivates the development of the multiplicative model of interactions.

- Multiplicative model: The reduction factors in the multiplicative model are obtained by taking the product of the actual functionalities of the components on which a given facility depends raised to their respective interaction coefficients, i.e.,

$$RF_1 = \prod_j (F^{j,act}(t))^{\gamma_{ji,mult}} \quad (3.8)$$

$$RF_2 = \prod_j (F^{j,act}(t))^{\beta_{ji,mult}} \quad (3.9)$$

Equations 3.8 and 3.9 imply a series system because if any of the components on which a facility depends on have zero functionality, its functionality and recovery rate go to zero as well. This may be extreme and gives an upper bound on the effect of interactions. This also poses a potential problem since if there are two components which depend on each other and if the functionality of one of them goes to zero, then the functionality and recovery rate of both go to zero and they never recover. This situation is avoided by allowing only “one-way” interactions, i.e., if component

i depends on j , the dependence of j on i is not allowed. Despite the deficiencies of the multiplicative model, it is considered to be more logically correct than the additive model, since the interaction effects do not decrease simply by considering more components. Thus, the multiplicative model of interactions is adopted in the methodology.

Data and Parameters

- Recovery parameters are obtained for the 7 occupancy classes (residential, commercial, heavy and light industry, high technology, food & drug and chemical industry). Recovery parameters are also obtained for two types of bridges (major - span ≥ 500 feet and conventional - span ≤ 500 feet), pavements and utility lifelines (transmission towers). Except for conventional bridges, ATC-13 (1985) is the source for all the components. In the case of conventional bridges, ATC-13 (1985) gives the rebuilding time as 2 years, which is considered to be rather long. Hwang et al. (2000) provide recovery data for ordinary bridges and estimate the recovery time to be about 6 months. This is considered to be a more realistic estimate and is used in the methodology.
- The “physical” functionality of a component is taken to vary with time as $F^{i,phy}(t) = at^b + c(D)$, $0 \leq F^{i,phy}(t) \leq 1$, where a and b are recovery parameters and $c(D)$ is the loss-of-function relation which depends on the damage ratio D . In the case of the macroseismic approach D is the building damage ratio. In the case of the engineering approach, D is taken to be the structural damage ratio. $c(D)$ is assumed to be of the form $c_0 * D + c_1 + c_2/D$. The parameters a , b , c_0 , c_1 and c_2 are estimated from fits to the ATC-13 (1985) data (Hwang et al. (2000) in the case of conventional bridges). ATC-13 (1985) gives times to 30%, 60% and 100% functionality for different damage states for each occupancy class. The parameters a and b are obtained from fits to this data. Figure 3-11 shows the fit to the ATC-13 (1985) data for the residential occupancy class. $c(D)$, which

is the intercept of the recovery curve with the functionality axis (y axis) is then obtained from the fitted curves for each damage ratio. c_0 , c_1 , and c_2 are obtained from a least squares fit to the plot of $c(D)$ vs D . Figure 3-12 shows this for the residential occupancy class.

- The residential, commercial and industrial occupancy classes are considered to be dependent on the utility and transportation lifelines. In addition, the commercial and industrial sectors are also assumed to depend on the residential sector, which coarsely models the labor requirements of these sectors. The inter-industry interactions and the interactions of the industries with the commercial sector are quantified separately in the economic input-output model (explained later). ATC-13 (1985) provides certain factors which give the effect of the loss-of-functionality of various lifelines on the functionalities of the residential, commercial and industrial sectors. The interaction model used by ATC-13 (1985) is similar to the additive model and therefore these values correspond to $\gamma_{ji,add}$. However, the literature lacks information regarding the corresponding interaction coefficients in the multiplicative model ($\gamma_{ji,mult}$), which is used in the methodology. The literature also lacks data regarding the effect of the residential sector on the other sectors as well as data on the interaction coefficients which affect the rate of recovery ($\beta_{ji,add}, \beta_{ji,mult}$). Therefore, the interaction coefficients ($\gamma_{ji,mult}, \beta_{ji,mult}$) in the multiplicative model are judgmentally set to 1. Sensitivity of the losses to the interaction coefficients is examined in Chapter 4.
- The ATC-13 (1985) estimates assume that reconstruction/repair would follow ordinary non-emergency schedules and that unlimited resources are available for reconstruction. However, in the event of an earthquake this is clearly not the case. There are limited resources which may constrain the recovery rates of sectors. In addition, the post-earthquake recovery rate itself could be a decision variable depending on rebuilding priorities and policies, as a result of which some sectors could experience faster recovery

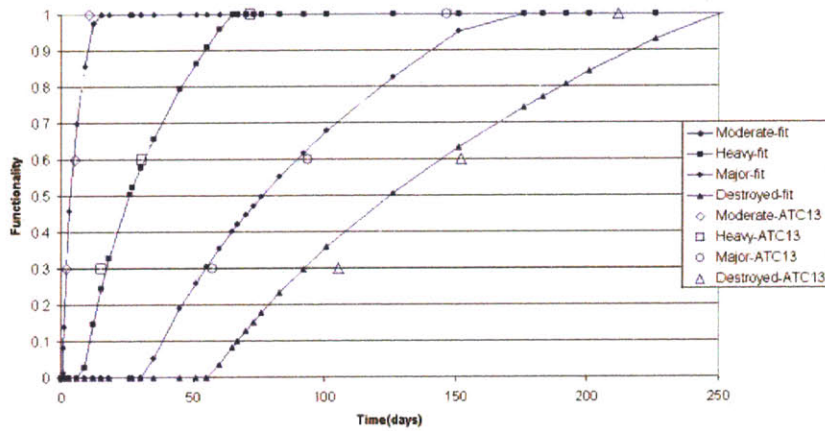


Figure 3-11: Estimation of the recovery parameters a and b for the residential occupancy class

and others slower recovery relative to their “normal” rates. The effects of speeding up or slowing down the recovery rates of certain sectors are examined in Chapter 4.

4. Economic Input-Output Model: The economic input-output model quantifies the inter-industry interactions and allows calculation of the net exports and imports from productions and domestic consumptions. The economic activity of the analysis regions is characterized by the production of each of the economic sectors. Each economic sector uses goods and services from other sectors to carry out production. This constitutes the inter-industry demand. In addition, there are domestic consumptions of the outputs of the economic sectors, which constitute the final demand. An analysis region therefore imports or exports a commodity depending on whether its production is smaller or greater than the total demand. The net exports are obtained using the standard Leontief model (Leontief and Strout (1963)) given by :

$$(I - A)X - c = b \quad (3.10)$$

where:

I is the identity matrix ($K \times K$); K is the number of economic sectors considered

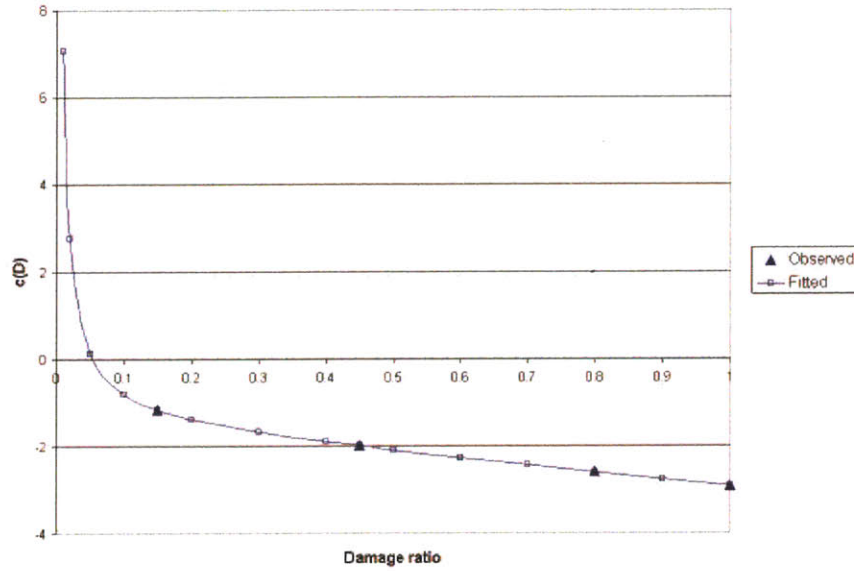


Figure 3-12: Estimation of the recovery parameters c_0 , c_1 and c_2 for the residential occupancy class

in the analysis

A is the input-output matrix ($K \times K$); element a_{ij} is the total output (in dollars) of industry i required to produce \$1 of output from industry j

X is the vector of productions in \$ of the economic sectors ($K \times 1$)

c is the vector of domestic consumptions in \$ of the economic sectors ($K \times 1$)

b is the vector of net exports (negative if imports) ($K \times 1$)

Data and parameters

- As noted earlier, 13 economic sectors (from Okuyama et al. (1999)) are considered in the analysis. Table 3.6 lists these sectors.
- The input-output matrix (A) is from Sohn et al. (2001a) and is given in Table 3.10. The elements of row i give the output of sector i used by the other sectors for their productions, while the elements of column j give the outputs of the other sectors used by sector j for its production. Table 3.10 indicates that most sectors depend highly on the Commercial/Services sector (sector 13), while it has a low dependence on other sectors.

- Sohn et al. (2001a) estimate the input-output matrix using the column coefficient model⁴, assuming identical interindustry structure at all regions. This methodology similarly considers the input-output model to be applicable at all the analysis regions and at the national level.
- At the national level, annual domestic consumptions for the 13 economic sectors are obtained from the Regional Economics Applications Laboratory (REAL) (see Sohn et al. (2001a)). The national values are then divided among the analysis regions in proportion to each region's population.
- The annual productions X are obtained at the national level from the annual domestic consumptions using $(I - A)X = c$. This assumes that the U.S is a closed system, without any exports or imports. This is a rough approximation, but necessary for simplifying the analysis. The national productions are then disaggregated to the analysis regions proportional to each region's share of the national values. The regional shares are obtained from the Commodity Flow Survey (CFS) '97 (Bureau of Transportation Statistics (1999)) and HAZUS (2000) data in the manner described below: The CFS'97 data is at the state level and gives shipments of commodities originating from a state and shipped to other states or to destinations within the state. This is disaggregated to the county level by population. Economic data at the county level is available from HAZUS (2000). Both these data sources are required as each does not completely characterize the economic activity of a region. For example, the CFS'97 data does not detail activity in the "construction" or "services" sectors, which are among the 13 economic sectors considered in the methodology. HAZUS (2000) on the other hand, classifies certain sectors in a very coarse manner, which is unsuitable for the level of detail used in the methodology. For example, HAZUS (2000) groups all manufacturing industries into a single sector and gives the total economic output of all the manufacturing

⁴An advanced econometric analysis technique; refer Moses (1955) and Okuyama (1997) for more information

industries, while this methodology considers different types of manufacturing industries such as primary metals, fabricated metals, durables etc. and requires the productions of each of them separately. Therefore, the CFS'97 data is combined with the HAZUS (2000) data to obtain the economic activity of each county. Finally, the data for the counties are aggregated to obtain the productions at each analysis region. The productions obtained at the analysis regions from CFS'97 and HAZUS (2000) give a fair indication of a region's share of the national productions. However, they may not be numerically accurate as they are obtained by combining data from different sources. Therefore, the productions obtained from CFS'97 and HAZUS (2000) are not used as such in the methodology. Rather they are only used as indicators of each region's share of the national productions and are used to disaggregate the national values to the analysis regions. The productions are disaggregated to the analysis regions as:

$$X_r^k = \frac{X_r^{k,CFS-HAZUS}}{X_{Total}^{k,CFS-HAZUS}} X^k \quad \forall k, r \quad (3.11)$$

where:

X_r^k is the production of commodity k at region r

$X_r^{k,CFS-HAZUS}$ is the production of commodity k at region r obtained from the CFS'97 and HAZUS (2000) data

$X_{Total}^{k,CFS-HAZUS}$ is the total production (aggregated over all analysis regions) of commodity k obtained from the CFS'97 and HAZUS (2000) data

X^k is the production of commodity k at the national level obtained from the REAL domestic consumptions

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 3.10: A Matrix (*Source:* Sohn et al. (2001a))

5. **Network Analysis Model:** The network consists of the highway intersections (nodes) with the highway segments (links) connecting them. As noted earlier, each analysis region is associated with the highway node closest to its centroid. The net exports/imports of a node are the totals for the analysis regions assigned to it. If a node has no analysis regions assigned to it, then it has no net exports or imports; it is simply a transshipment node. A network optimization algorithm is used to route the commodities (goods produced by the economic sectors) on the network at the minimum cost to meet the nodal requirements. A network optimization algorithm assumes that the network is balanced (exports equal imports) and has sufficient capacity. While this is true pre-earthquake, it is not necessarily so post-earthquake. The network becomes unbalanced because of the reduced production of the damaged economic sectors and the decrease in the network capacity due to link damage. A “virtual” node is added to balance the network. It is assigned the net excess or deficit. The virtual node is connected to all the highway nodes by virtual links. The virtual links are considered “indestructible”, and have high transportation costs (cost per unit flow) and capacities. The virtual links ensure that the network has sufficient capacity at all times.

The manner in which the network flows are determined and the imports and exports assigned to the regions is described in Section 3.3.

Data and parameters

- *Pre-earthquake link capacity calibration* : Setting the link capacity based on the number of lanes results in low pre-earthquake link utilizations (flow/capacity). This is because passenger flows and cross-hauling⁵ are not considered in the methodology. Low pre-earthquake link utilizations underestimates the importance of the transportation network in the post earthquake scenario, since even at reduced capacities most links would be able carry all the flows. In order to better model network congestion and

⁵The flow of the same commodity in both directions between two nodes/regions.

the effects of network disruption, the link capacities are set as follows:

- Links with bridges on them: Link capacities in the New Madrid region, where bridges are modeled, are set this way. The average daily traffic (ADT) data on the bridges is available from the NBI (Federal Highway Administration (FHWA) (1995)). The link capacity is set to be that required to carry 20% of the minimum ADT on its bridges. This is assumed to be the capacity required to carry the traffic excluding the passenger flows and flows due to crosshauling.
- Links without bridges on them: These are typically links outside the New Madrid region, where bridges are not modeled. For links with less than 50% utilization, capacity is set as the maximum of 10% of the physical capacity (based on the number of lanes) and the capacity required to carry twice the flow. A lower bound on capacity is required (10% of physical capacity) since some links have no pre-earthquake flows on them. Setting the capacity based on pre-earthquake flows alone would result in these links having zero capacity, which is equivalent to deleting them from the network. However, these links could be important for re-routing commodities in the post-earthquake scenario.

The capacity calibration parameters were determined by trial-and-error. For the given values, the average link utilization under pre-earthquake conditions is about 50%, which is reasonable.

- *Modeling the effect of secondary roads* : The transportation network does not include many of the state highways and most of the county roads. These could be critical in the post-earthquake scenario for re-routing traffic around the damaged interstate highways, thus reducing the disruption in commodity flows. For example, there might be a few bridges on an interstate that are damaged and cannot carry traffic. However, it is unreasonable to assume that the interstate gets closed down because of this. Setting the link capacity to be the minimum of the pavement and bridge

capacities makes this assumption, which is unrealistic. Most likely, there would be a re-routing of traffic around the damaged bridges, using nearby secondary roads, thus reducing the impact of the bridge closures. This is modeled in a very coarse manner by setting the capacity of each transportation link in the post-earthquake scenario as:

$$\text{Link capacity} = \min(\text{Pavement capacity}, \text{Bridge capacity}) \quad (3.12)$$

$$\text{If}(\text{Link capacity} \leq \rho * \text{Undamaged link capacity}) \quad (3.13)$$

$$\text{Link capacity} = \min(\rho * \text{Undamaged link capacity}, \text{Pavement capacity}) \quad (3.14)$$

Therefore, while the link capacity is set to the minimum of the pavement and bridge capacities, each bridge capacity is not allowed to be less than ρ ($0 \leq \rho \leq 1$) times the undamaged link capacity. Figure 3-13 shows this graphically. As can be seen, bridges typically take much longer to recover functionality compared to pavements. Setting the link capacity using Equation 3.12 alone reduces the link capacity for an extended period of time. Including conditions 3.13 and 3.14 in the calculation of the link capacity reduces the effect bridge closures. ρ is judgmentally set to be 0.25. Loss sensitivities to the “re-routing” parameter ρ are given in Chapter 4.

Calibrating the pre-earthquake link capacities and modeling the effects of secondary roads are improvements in the methodology of Gupta (2001). Gupta (2001) sets the lane capacities based on the number of physical lanes and calculates the link capacity to the minimum of the pavement and bridge capacities.

The component models along with the model data and parameters have been described. Next, the manner in which these models are integrated to estimate the losses is explained.

3.3 Analytical Framework

The loss estimation methodology is comprised of the following 5 steps:

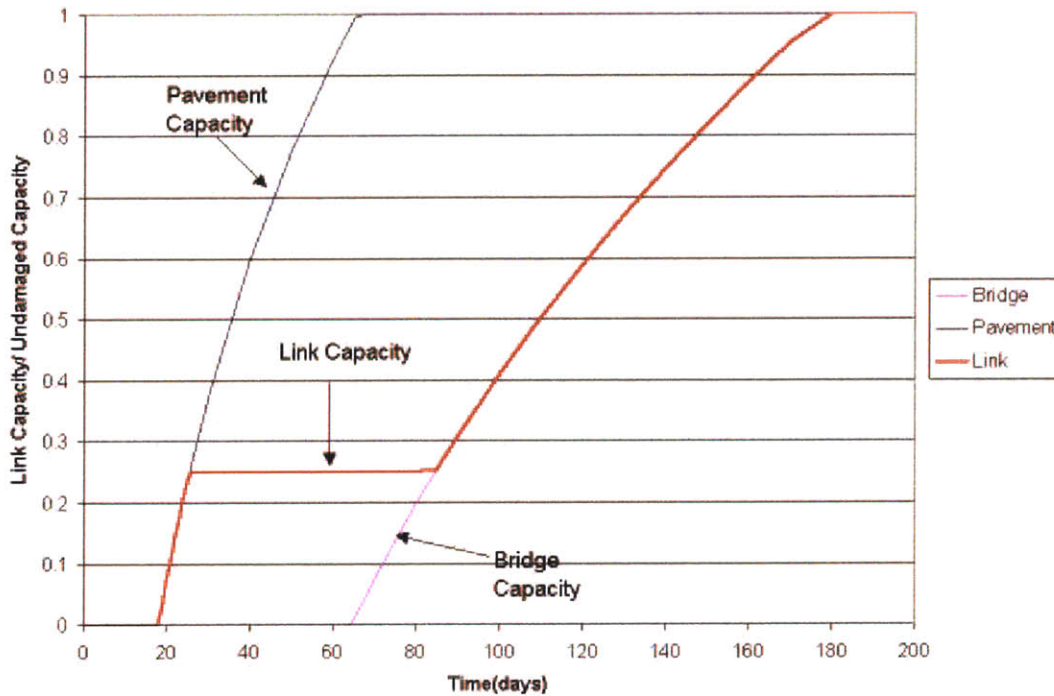


Figure 3-13: Setting of the link capacity to model the effect of secondary roads

Step 1: Damage and functionality initialization Time since the earthquake occurrence is discretized as $t_0 = 0^+, t_1, t_2, \dots$. At time t_0 , the local ground motion intensity at each analysis region and transportation link is calculated using the attenuation relations. Damage to the infrastructure elements (buildings, lifelines, bridges and pavements) is obtained using the fragility curves. Loss-of-function relations are used to initialize the functionality.

Steps 2 and 3: Node-Network Iterations . These are a sequence of iterations to determine whether the transportation network can provide each region with the required net exports/imports. If the net exports/imports cannot be met then the region will adjust its productions/consumptions to meet the network capacity constraints. The iterations involve the following steps⁶:

- i: For each analysis region, the productions are calculated taking into account

⁶In the node-network iterations, all variables are functions of time. However, the time dependence is not shown explicitly for the sake of notational convenience

the reduced functionality of the economic sectors. The productions are calculated as :

$$X_r^k = X_r^{k,preEQ} F_r^{k,act}(t) \quad \forall k, r \quad (3.15)$$

where:

X_r^k is the production of economic sector k per unit time in region r (in \$)

$X_r^{k,preEQ}$ is the pre-earthquake production of sector k per unit time in region r

$F_r^{k,act}(t)$ is the functionality of sector k in region r at time t ; calculated using Equation 3.4

As the literature lacks data on the change in domestic consumptions after earthquakes, they are assumed to be the same as the pre-earthquake values, i.e., $c_r^k = c_r^{k,preEQ}$. The capacity of each transportation link is calculated using Equations 3.12, 3.13 and 3.14.

- ii: The productions are increased uniformly across all regions to balance the deficit created in the damaged regions. This is a very coarse representation of the buffering effects of inventory, increased economic output from certain regions within the country and increased foreign imports, which have the potential to absorb some of the supply shock from the earthquake affected regions. It is beyond the scope of the methodology to model these different buffering effects. Instead, the methodology assumes that there is a certain slack in the industrial productions at *all* regions and that the industries can increase their economic output up to the slack limit to make up for the decreased productions in earthquake affected regions. The productions are increased to minimize the difference between the productions and the total demand (industrial demand and domestic consumption) of all commodities at the national level, with the constraint that each economic sector cannot increase its production beyond its slack limit. The linear programming formulation of this problem is given below:

$$\min \sum_{k=1}^K \|d^k\| \quad (3.16)$$

s.t

$$(I - A)X^{total}factor - c^{total} + d = 0 \quad (3.17)$$

$$0 \leq factor^k \leq slack^k \forall k \quad (3.18)$$

$$(3.19)$$

where:

I is the identity matrix

A is the input-output matrix

$X^{total}factor$ is the vector of the increased productions of the economic sectors; an element of this vector, $X^{k,total}factor^k$ is the product of the national production of economic sector k ($X^{k,total}$) times the percentage increase in its production($factor^k$)

c^{total} is the vector of the domestic consumptions of the economic sectors aggregated over all analysis regions

$slack^k$ is slack in the production of economic sector k ; judgmentally set to 1.05, which implies a 5% slack in production

$\|d^k\|$ is the absolute difference between the production and the total demand for sector k . Minimizing $\sum_{k=1}^K \|d^k\|$ therefore minimizes the difference between the production and total demand for all the sectors. $\sum_{k=1}^K \|d^k\| = 0$ implies that the productions can be successfully increased to meet the total demand. $\sum_{k=1}^K \|d^k\| \neq 0$ indicates that some sector has reached its slack limit. Therefore, the increase in productions is not sufficient to meet the total demand and there is some net deficit. In either case, $factor^k$ gives the required increase in the production of each economic sector to minimize the difference between the productions and the total demands at the national level.

- iii: The factors obtained from the LP (3.16) are applied uniformly to the economic sectors in each region. The increased production of commodity k at region r is given by $X_r^k factor^k$. The productions and consumptions of the associated analysis regions are then aggregated at the highway nodes.

The productions and consumptions at the nodes are given by:

$$X_i^k = \sum_{r \in R_i} X_r^k factor^k \quad \forall k, \forall i \quad (3.20)$$

$$c_i^k = \sum_{r \in R_i} c_r^k \quad \forall k, \forall i \quad (3.21)$$

where:

X_i^k is the production of sector k at node i

$X_r^k factor^k$ is the (increased) production of sector k at region r

c_i^k is the domestic consumption of sector k at node i

c_r^k is the domestic consumption of sector k at region r

R_i is the set of analysis regions attached to node i

Given the nodal productions and consumptions, the net exports and imports (b_i^k) are calculated using the economic input-output relation (Equation 3.10).

- iv: A min-cost-multi-commodity flow (MCMCF) problem is solved on the network to satisfy the nodal requirements by routing the commodities at the least cost. The linear programming formulation of this problem is:

$$\min \sum_{k=1}^K \sum_{(i,j) \in A^+} c_{ij}^k x_{ij}^k \quad (3.22)$$

s.t

$$\sum_{j:(i,j) \in A^+} x_{ij}^k - \sum_{j:(j,i) \in A^+} x_{ji}^k = b_i^k / \lambda^k \quad \forall k, i \quad (3.23)$$

$$\sum_{k=1}^K x_{ij}^k \leq u_{ij} \quad \forall (i, j) \in A^+ \quad (3.24)$$

$$x_{ij}^k \geq 0 \quad \forall (i, j), k \quad (3.25)$$

where:

c_{ij}^k is the cost per unit flow of commodity k on link (i, j) ; in all our analysis

c_{ij}^k is taken to be the link length

x_{ij}^k is the flow of commodity k on link (i, j) in truck units (trucks/day)

b_i^k is the net export/import of commodity k at node i in \$

λ^k is a factor for converting \$ commodity values to vehicle units for commodity k ; in our analysis λ^k is set as 10500\$/truck based on values given in Sorratini (2000)

u_{ij} is the link capacity in trucks units, set to be 12000 trucks/day/lane

A^+ is the set of all links, including the virtual links

The objective function 3.22 minimizes the total cost of routing all the commodities on the network. Constraint 3.23 is the flow balance constraint, which states that the outflow less the inflow of a commodity at a node is its net export. Constraint 3.24 is the bundling constraint on the network links, which states that the total flow of all commodities on a link should not exceed its capacity. This constraint couples the different commodities and increases the complexity of the problem; in its absence the problem can be solved as K independent min-cost flow problems. Finally, Constraint 3.25 is the non-negativity constraint on the commodity flows.

- v: The actual net exports/imports at the nodes are determined. These are the commodities transported through the “real” links, i.e., the highways. The commodities transported through the virtual links are not actually received at/ sent from the node. The actual net exports/imports at the nodes are given by:

$$b_i^{k,actual} = \lambda^k \left(\sum_{j:(i,j) \in A} x_{ij}^k - \sum_{j:(j,i) \in A} x_{ji}^k \right) \quad \forall k, i \quad (3.26)$$

where:

$b_i^{k,actual}$ is the actual net export/import of commodity k at node i (in \$)

A is the set of “real” links

- vi: In this step, the nodal net exports are set to be as close as possible to the actual net exports. This is done by adjusting the productions and consumptions at each node, which determine the nodal net exports, to minimize the difference between the actual and the nodal net exports. However, the productions and consumptions are not “free” variables; they

are constrained to be non-negative and less than the maximum possible values (obtained from Equations 3.20 and 3.21). The entire problem can be formulated as the following linear program (LP):

$$\max -C_1 \sum_{k=1}^K d_i^k + C_2 \sum_{k=1}^K X_i'^k + C_3 \sum_{k=1}^K c_i'^k \quad (3.27)$$

s.t

$$(I - A)X_i' - c_i' \pm d_i = \pm b_i^{actual} \quad (3.28)$$

$$0 \leq X_i'^k \leq X_i^k \quad \forall k \quad (3.29)$$

$$0 \leq c_i'^k \leq c_i^k \quad \forall k \quad (3.30)$$

$$d_i^k \geq 0 \quad (3.31)$$

where:

C_1 , C_2 and C_3 are given non-negative constants

d_i^k is the difference between the actual and nodal net export of commodity k at node i

$X_i'^k$ is the adjusted production of sector k at node i

X_i^k is the maximum possible production of sector k at node i considering the level of damage at that node. X_i^k is obtained from Equation 3.20

$c_i'^k$ is the adjusted domestic consumption of sector k at node i

c_i^k is the maximum domestic consumption of sector k at node i ; it is obtained from Equation 3.21

X_i' , c_i' and d_i are the vectors of $X_i'^k$, $c_i'^k$ and d_i^k , respectively

b_i^{actual} is the vector of actual net exports at node i ($K \times 1$)

The negative coefficient of d_i^k in the objective function 3.27 implies that it is minimized. By minimizing each d_i^k , the productions and consumptions of the economic sectors are set so that the nodal net exports are as close as possible to the values obtained from the network. In Constraint 3.28, the polarity of d_i^k is set to be the same as that of $b_i^{k,actual}$. This guarantees that the net export from the node is smaller or at most equal to the network values, which is necessary for convergence of the node-network iterations.

Constraints 3.29 and 3.30 specify the lower and upper bounds for the productions and consumptions respectively. The objective coefficients C_2 and C_3 determine how deficit in the net exports is apportioned among the economic sectors (thus hampering productions) and the population (thus reducing final consumptions). For example, a larger value of C_2 relative to C_3 makes the productions more attractive in the objective function. Therefore, the productions are kept close to the maximum values while the deficit is apportioned more among the domestic consumptions. These coefficients can be used as policy variables to dictate the share of the total deficit borne by the economic sectors and the population. In general, it is advantageous to keep the industries operational as their productions are used to satisfy at least in part the domestic demand and to speed up recovery. Assigning most of the deficit to the industries could result in decreased productions, causing a ripple effect where the productivity of the entire economy goes down, creating further shortages.

The LP outputs the values of the variables d_i^k , $X_i'^k$ and $c_i'^k$. If $\|d_i^k\| \leq \varepsilon \forall k$ where ε is a specified tolerance (strictly positive), then the difference between the nodal requirements and the actual net exports of all economic sectors is considered nil. In this case, the node is able to adjust its productions and consumptions to meet the network constraints and is said to be “balanced”. Otherwise, if there is some k for which $\|d_i^k\| \geq \varepsilon$, the node is not able to adjust its productions and consumptions to meet the network constraints and is said to be “unbalanced”. In physical terms, a node becomes unbalanced when it has to maintain its net exports of certain commodities while receiving very little imports of other commodities or vice versa.

- vii:** If there are any unbalanced nodes, steps (iv-vi) are repeated with modified nodal net exports given by:

$$b_i^k = b_i^{k,actual} - d_i^k \quad (3.32)$$

On the other hand, if all nodes are balanced, the node-network iterations are terminated. At convergence, the productions and consumptions of the analysis regions are obtained as:

$$X_r'^k = X_r^k \frac{X_i'^k}{X_i^k} \quad \forall r \in R_i, \forall i \quad (3.33)$$

$$c_r'^k = c_r^k \frac{c_i'^k}{c_i^k} \quad \forall r \in R_i, \forall i \quad (3.34)$$

where:

$X_r'^k$ is the production of sector k at region r at the end of the node-network iterations

X_r^k is the production of sector k at region r without considering network capacity constraints, i.e., prior to the node-network iterations

$c_r'^k$ is the domestic consumption of sector k at region r at the end of the node network iterations

c_r^k is the domestic consumption of sector k at region r without considering the network capacity constraints

R_i is the set of analysis regions attached to node i

Equations 3.33 and 3.34 reduce the productions and consumptions at the analysis regions proportionally to the corresponding reductions $(\frac{X_i'^k}{X_i^k}, \frac{c_i'^k}{c_i^k})$ at the associated highway node.

Step 4: Loss Calculation The indirect losses incurred during the current time step are calculated. These include losses due to reduced productions, reduced consumptions and increased transportation costs.

- Losses due to reduced productions and consumptions: These losses are given by:

$$IDL_{prod}(t) = \Delta t \sum_{k=1}^K \sum_{r=1}^R (X_r^{k,preEQ} - X_r'^k) \quad (3.35)$$

$$IDL_{cons}(t) = \Delta t \sum_{k=1}^K \sum_{r=1}^R (c_r^{k,preEQ} - c_r'^k) \quad (3.36)$$

where:

$IDL_{prod}(t)$ is the indirect loss due to reduced productions during the time step, summed over all commodities K and all analysis regions R

$IDL_{cons}(t)$ is the indirect loss due to reduced consumptions (unmet final demand) during the time step, summed over all commodities K and all analysis regions R

$X_r^{k,preEQ}, c_r^{k,preEQ}$ are the pre-earthquake productions and consumptions of sector k in region r

$X_r'^k, c_r'^k$ are the constrained productions and consumptions (from Equations 3.33 and 3.34)

Δt is the length of the time step

The losses at each time step are added up over time to get the total indirect economic and social⁷ losses. These losses may also be disaggregated in space and time and by economic sector.

- Losses due to the increased transportation cost: Estimating the losses due to the increased transportation cost is a little more involved compared to estimating the other losses. This is mainly due to the lack of a good indicator of the transportation related losses. The total transportation cost is not a good indicator as it actually decreases immediately after the earthquake. This decrease is caused by the fact that there are fewer goods flowing on the network due to the reduced transportation capacity and demand. The cost per unit shipped (total cost/total flow) is also deficient as an indicator. This is because most of the goods might flow locally, in the undamaged regions, with very little flow to the damaged regions. A measure of the increased transportation cost at any time t is obtained by comparing the cost of routing the commodities on the damaged network to that of routing the same commodities on an undamaged network. Clearly, the former is at least as great as the latter. The cost of routing the com-

⁷Taken to be the loss due to unmet domestic consumptions

modities on the damaged network may be higher as they may have to be routed along longer paths because of the reduced link capacities. Therefore, at each time step, after the node-network iterations have converged, an additional network analysis is carried out with the links at their undamaged capacities. The increased transportation cost is then obtained as:

$$IDL_{transp}(t) = \frac{TC_{damaged}}{TC_{undamaged}} \quad (3.37)$$

where:

$TC_{damaged}$ is the total transportation cost on the damaged network

$TC_{undamaged}$ is the total transportation cost on an undamaged network

- Direct Losses: In addition to the indirect loss calculation at each time step, at time $t = 0^+$, direct economic losses due to building, contents, bridge and pavement damage are evaluated. The direct economic loss is then obtained by multiplying the infrastructure damage by its replacement cost. The replacement costs for buildings, which are taken to be the construction costs, are obtained from the Means Square Foot Costs 2000 (Barbara Balboni (2000)). The Means publication provides cost information for over 70 types of residential, commercial, industrial and institutional buildings. The replacement costs for the occupancy classes used in this methodology are obtained by taking an average of the costs for the corresponding building types in the Means publication. Table 3.11 lists the replacement costs for the occupancy classes used in this methodology. The building replacement costs are broken down into repair costs for structural, non-structural acceleration sensitive and non-structural drift sensitive components proportionally to the HAZUS (2000) values⁸. Typically non-structural components make up 70-80% of the building value. As done in HAZUS (2000), the replacement costs for contents in residential, commercial and industrial buildings are taken to be 0.5, 1.0 and 1.5 times corresponding building re-

⁸HAZUS (2000) gives the costs for structural and non-structural components based on Means 1994

Occupancy Class	Replacement Value (\$/sq.foot)
Residential	100
Commercial	125
Heavy Industrial	80
Light Industrial	80
High Technology	100
Food&Drug	80
Chemicals	80

Table 3.11: Building replacement costs

Transportation System Component	Replacement Value (thous. \$)
Major Bridges	20,000
Continuous Bridges	5,000
Other Bridges	1,000
Pavements (per km per lane)	2,500

Table 3.12: Replacement costs of transportation system components (*Source: HAZUS (2000)*)

placement costs. The repair costs for bridges and pavements are taken from HAZUS (2000) and are given in Table 3.12.

The procedure for estimating the social losses due to casualties is similar to that in HAZUS (2000), with a few simplifications. The simplified procedure is from Jammalamadaka (2002a). HAZUS (2000) gives the distribution of the population in the different building types at the census tract level. Instead of re-aggregating this data to the analysis regions, the simplifying assumption made is that 40% of each region's population is in the residential buildings. The remaining 60% is divided among the commercial and industrial buildings proportional to the floor areas of these buildings in the region. HAZUS (2000) gives the casualty rates in each building class as a function of earthquake damage. The number of casualties is therefore estimated from the casualty rate, population in the building and the building damage. The casualties estimated in this manner are for the engineering approach. A corresponding procedure in the macroseismic approach has not been implemented at this time.

Estimation of the losses due to casualties and increased transportation costs are improvements in the methodology of Gupta (2001).

Step 5: Functionality Update Time is increased from t_i to t_{i+1} and the recovery model is used to update the functionalities of the various infrastructure components, taking into account the effects of interactions on the functionality as well as the recovery rate (using Equations 3.4 and 3.5).

Steps 2-5 are repeated until all the infrastructure elements have recovered completely.

3.4 Implementation and Numerical Issues

The loss estimation methodology is implemented in the C++ programming environment. Two non-commercial solvers - LPSOLVE⁹ and IPM (Castro (2000)) are used for solving the LP's and the multi-commodity flow problems, respectively.

- **Memory requirements:** The memory requirements are dictated by the number of analysis regions, highway nodes, links and bridges and the level of detail of the structural, occupancy and economic classifications used. The inventory, economic activity, population and soil data in the regions have to be stored in memory. Similarly storage space is required for the highway nodes (location), links (length, start and end nodes) and bridges (structural classification, link with which it is associated).
- **Run Times:** On a standard current desktop (Pentium III, 700MHz, 256Mb) typical run time is about 40 minutes (for the resolution in Gupta (2001), 152 regions, 484 nodes, 1448 links, 1958 bridges). The factors that affect run time include:

⁹LPSOLVE 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

- Size of the discrete time steps considered in the analysis

The size of the time steps affects the run times as at each time step, the node-network iterations have to be repeated. The analysis divides the time until complete recovery into several discrete time steps. Within each time step, the system is assumed to be in a constant state. Immediately following the earthquake, when the system state changes rapidly over time, smaller time steps are taken to maintain accuracy. At later periods, when the recovery rate is more gradual, larger time steps are taken to speed up the procedure without loss of accuracy.

- Size of the network, number of commodities: The running time of the network optimization algorithm (IPM, Castro (2000)) increases non-linearly with the size of the network (number of nodes and links) and the number of commodities considered. The solution time becomes very large for networks having more than 1000 nodes. The run time of the LP solver (LPSOLVE) increases linearly with the number of nodes, as it has to be executed for more nodes.
- Intensity of the earthquake: The run time increases with the intensity of the earthquake. For a large earthquake, there is higher damage, more areas with damaged and longer time to full recovery. Thus, more time steps have to be considered. In addition, the running time per time step also increases. This is because there are greater number of unbalanced nodes in the network and more iterations are required until convergence.
- Tolerances in the network: The tolerance ϵ in the node-network iterations determines whether a node is considered at equilibrium. Smaller tolerances might result in more nodes being declared unbalanced, as a result of which more iterations would be needed until convergence.
- Capacity constraints in the network: The run time of the network optimization algorithm increases as the capacity constraints become tighter. Tighter capacity constraints in the network causes links to reach capacity,

and hence alternative commodity routings have to be determined, increasing the solution time.

The next chapter presents and discusses the results for a scenario New Madrid earthquake.

Chapter 4

Results

This chapter presents results for scenario New Madrid earthquakes. This chapter focusses largely on understanding how results vary with the resolution of the model. Two different model resolutions are considered, a “low” resolution and a “high” resolution. A description of the two model resolutions is first given. Results obtained using the alternative resolutions are then presented and discussed. In addition, the sensitivity of losses to alternative ground motion and fragility evaluations (macroseismic vs engineering approach) and selected model parameters (fragilities, re-routing parameter, interaction coefficients etc.) are examined. Finally loss reductions from various mitigation measures such as the retrofitting of buildings and bridges are discussed.

4.1 Spatial Discretization/Network Resolution

The spatial discretization of the analysis regions and the resolution to which the transportation network is represented are important issues as they affect the accuracy of the loss estimates.

The spatial discretization of the analysis regions can lead to errors in the loss estimates because of

a) The aggregation of property within the analysis regions - all properties in an

analysis region are treated as being concentrated at the centroid¹ of the region

b) The non-linearity in the attenuation of damage with distance.

To illustrate this, consider the attenuation of damage with distance shown in Figure 4-1. This is the damage-distance relation for timber buildings in the macroseismic approach. Consider an analysis region with centroid at 10km, and property (say timber buildings) located at distances of 5 and 15km. Calculating damage assuming the property is concentrated at the centroid overestimates the property damage in the region in this case. The error is greater if there is an uneven distribution of property, i.e., more property at 15km than 5km or vice versa. Similarly damage may be underestimated or there may be no error. In this case, if all the property in a region is located within 10km, then the actual location of property is immaterial as damage is constant within 10km. Error in assessing the damage leads to errors in direct and indirect losses, which can be reduced by having a fine spatial discretization of the analysis regions. With reference to the earlier example, there is no error if the analysis region is split into two sub-regions with centroids at 5 and 15km.

The resolution of the network is important since it affects the indirect losses resulting from commodity flow disruption. In a sparse network, there might be only a single path between two regions and damage to any of the links on this path disconnects them. This disrupts the commodity flows between the regions, resulting in indirect economic losses at those regions. This could be erroneous since there might be multiple paths between the regions, i.e., redundancy in the network, and therefore there may be no disruption in commodity flows due to damage to a few links. The network redundancy is increased by modeling it in greater detail and this reduces the error in the indirect losses stemming from overestimating the disruption in commodity flows. Errors in a sparse network also come from assigning the regions to the highway nodes. As mentioned in Chapter 3, each analysis region is associated with the highway node closest to its centroid. Consider the regions and the highway nodes

¹population centroid, which is the mean of the geometric centroids of the counties comprising the region weighted by the counties' population

in Figure 4-2. Regions 221, 218, 434 and 430 are all associated with highway nodes closer to the epicenter relative to their centroids. Therefore the model overestimates the disruption in commodity flows in these regions. In contrast, regions 435 and 202 are associated with highway nodes farther away from their epicenter than their centroids and so the model underestimates the disruption. This error can be eliminated by increasing the density of the network in the region. Figure 4-3 illustrates this.

While increasing the resolution of the model improves the accuracy of the results to some extent, going to very fine resolutions is not necessarily optimal. Modeling assumptions and model data that are valid at the macroscopic level need not be valid at the microscopic level. For example, building fragility curves are reliable as predictors of damage for large population groups and not for a specific facility. In addition, the unavailability of inventory and economic data at very disaggregate levels prevents one from going to very fine resolutions. Therefore, the accuracy of the results cannot be improved by increasing the spatial resolution alone; better models and more accurate data are required as well. Computational and storage requirements also limit the degree to which the resolution can be increased.

The effects of increasing the model resolution are analyzed, taking into account the above mentioned limitations. The resolution of the analysis regions and the transportation network in the model of Gupta (2001) has been described in Chapter 3. The county is the lowest geographical unit considered and each analysis region typically consists of a number of counties. The transportation network includes all the interstate highways augmented by some state highways in the New Madrid region. These models are referred to as the “low” resolution models of the analysis regions and the transportation network.

The “high” resolution models of the analysis regions and the transportation network are obtained by decomposing the analysis regions into smaller units and adding more detail to the network close to the scenario earthquake epicenter. In this analysis, the primary scenario considered is an earthquake located in Shelby County, Tennessee. Therefore, the resolution of the analysis regions and the transportation network is increased around Shelby County. Figure 4-4 shows the region where the

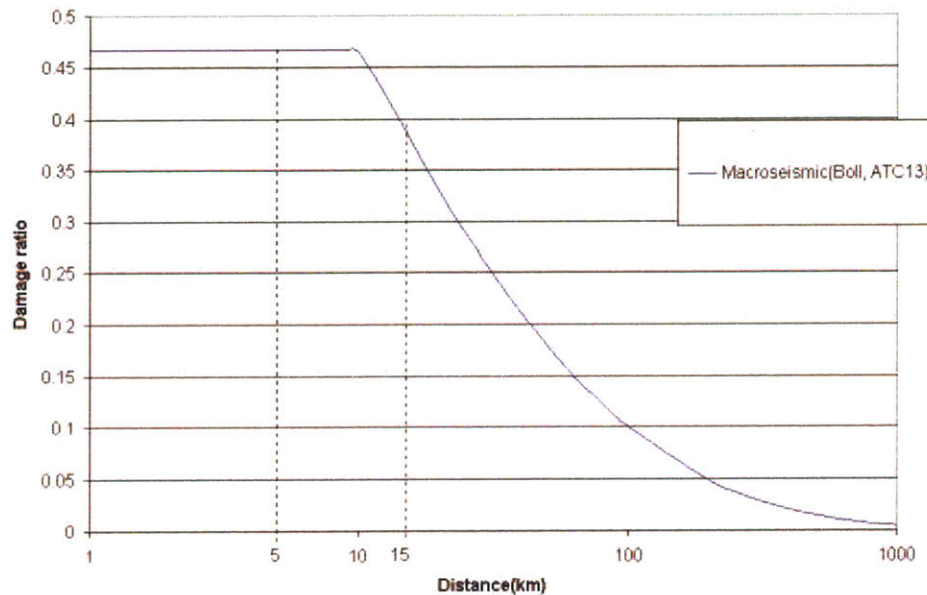


Figure 4-1: Non-linearity in the attenuation of damage with distance

model resolution is increased. It extends roughly 100km east, west and south of the centroid of Shelby County and 200km north and so captures most of the earthquake damage. The greater extent in the northern direction is to make the model applicable to other scenario earthquakes in the New Madrid region as well.

“High” resolution model of analysis regions: The resolution of the analysis regions is increased differently depending on location. Within Shelby County, the resolution is increased to the census tract level. Other regions are modeled at the county level.

Shelby County is specifically considered as the scenario earthquake epicenter is located within it. Besides, as there is a large amount of property in Shelby County, it is important to model its spatial distribution. In the low resolution model, Shelby County is considered to be a single analysis region, with property and economic activity treated as being concentrated at its centroid. In the high resolution model, it is decomposed into a number of finer analysis regions. The finer regions are obtained by aggregating the census tracts in Shelby County

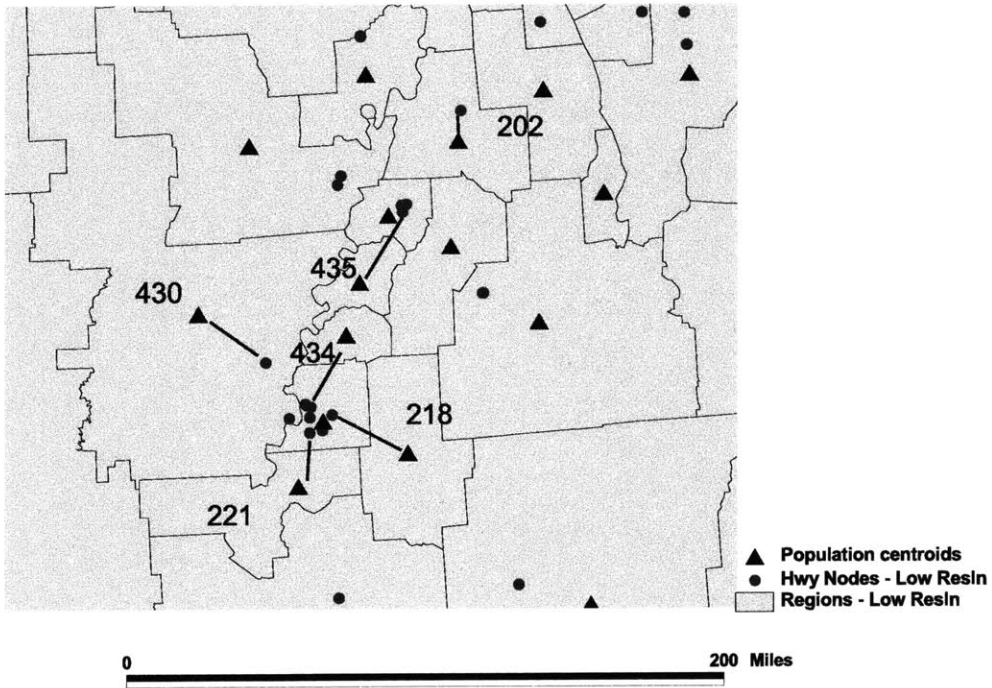


Figure 4-2: Assignment of regions to highway nodes in a sparse network

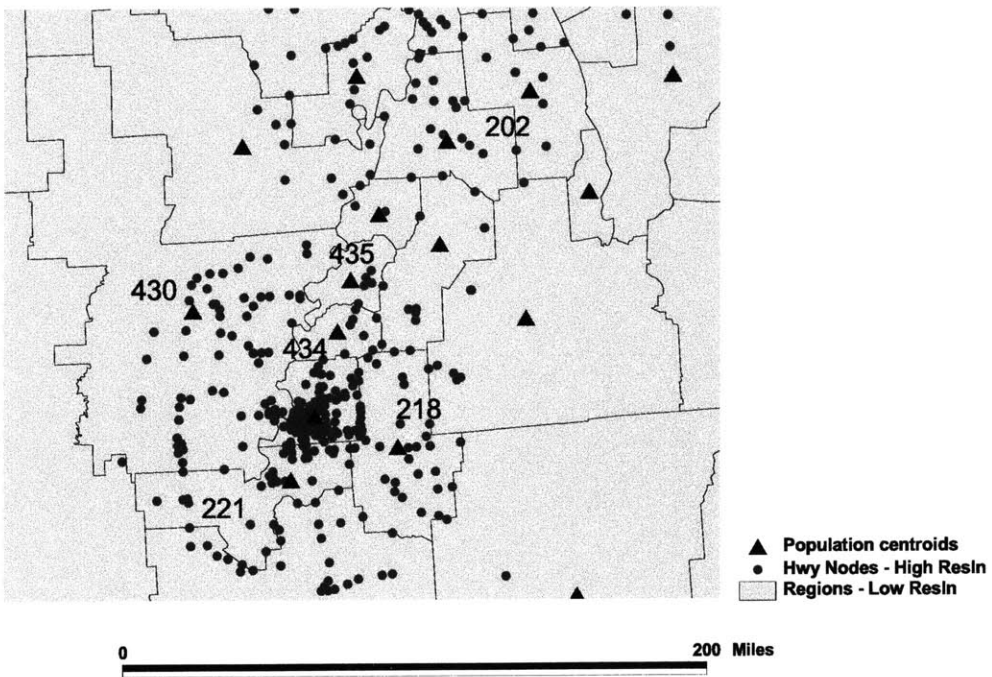


Figure 4-3: Assignment of regions to highway nodes in a dense network

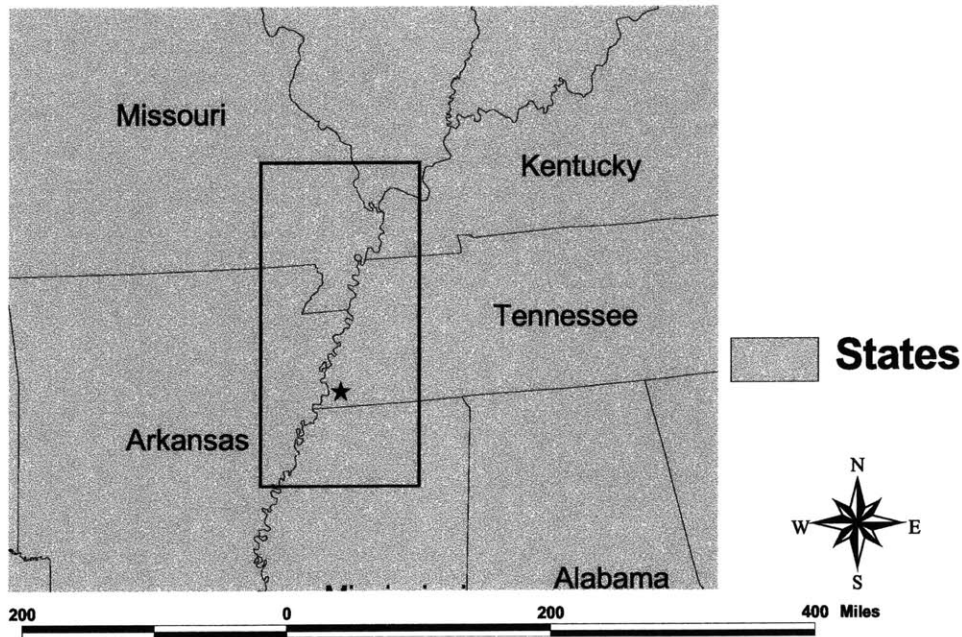


Figure 4-4: Area of increased resolution

around the nodes of the refined transportation network in the manner described in Chapter 3. Figure 4-5 shows the census tracts within Shelby County, and Figure 4-6 shows the analysis regions obtained by aggregating them.

Counties in the region of increased resolution excluding Shelby County have relatively low levels of inventory and economic activity. Therefore, they are considered to be individual units in the high resolution model; for them further disaggregation to the census tract level is not done. Figure 4-7 shows the analysis regions in low resolution model and Figure 4-8 shows the finer regions obtained by decomposing them.

The population of the refined analysis regions is obtained from the 1990 U.S. Census of Population and Housing. The building inventory and economic activity are obtained by disaggregating the corresponding values of the “parent” analysis region (the analysis region decomposed to yield the finer regions) proportional to population. For example, the building inventory and economic activity of Shelby County is divided among the analysis regions comprising it

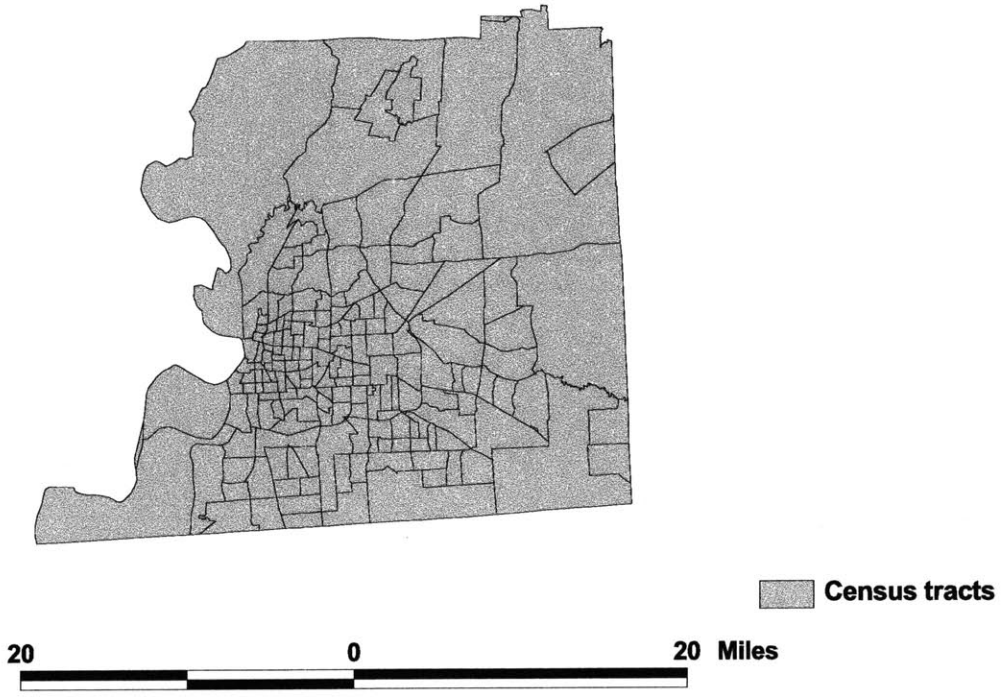


Figure 4-5: Shelby County census tracts



Figure 4-6: Shelby County analysis regions

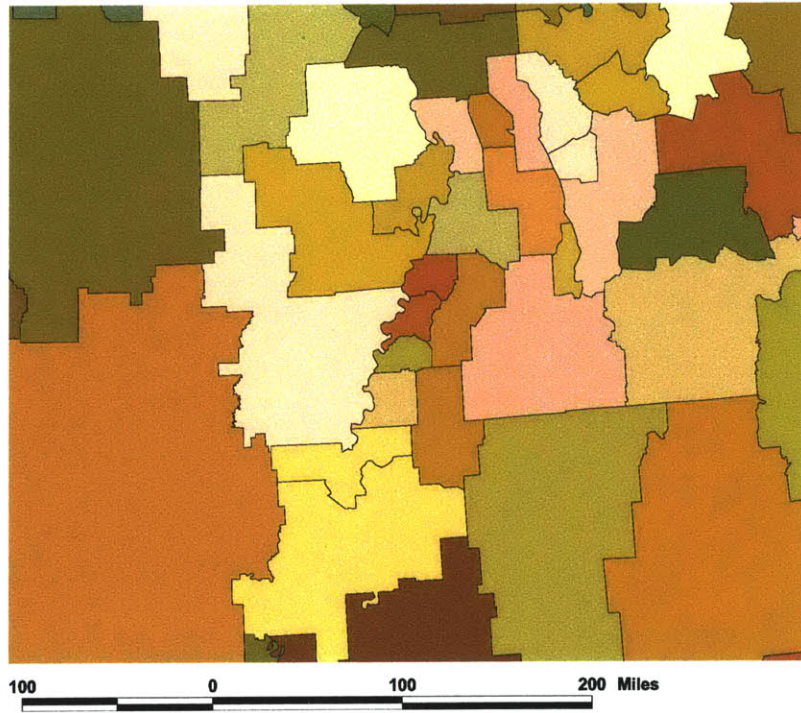


Figure 4-7: Low resolution analysis regions

proportional to each region’s population. This method of disaggregation is chosen as a simpler alternative to the more computationally intensive method of obtaining the inventory at the refined regions by re-aggregating the census tract inventories from HAZUS (2000). The high resolution model of analysis regions has about 300 regions, which is roughly twice the number in the low resolution model.

“High” resolution model of the network: Consistent with the finer discretization of analysis regions, there is also greater resolution of the network in Shelby County. Within Shelby County, the U.S highways and county roads are modeled in addition to interstate and state highways. Outside Shelby County, within the region of increased resolution, most of the state highways are modeled. The roads in the refined network are extracted from the transportation network inventory of Mid-America states available at the Center for Geographic Infor-

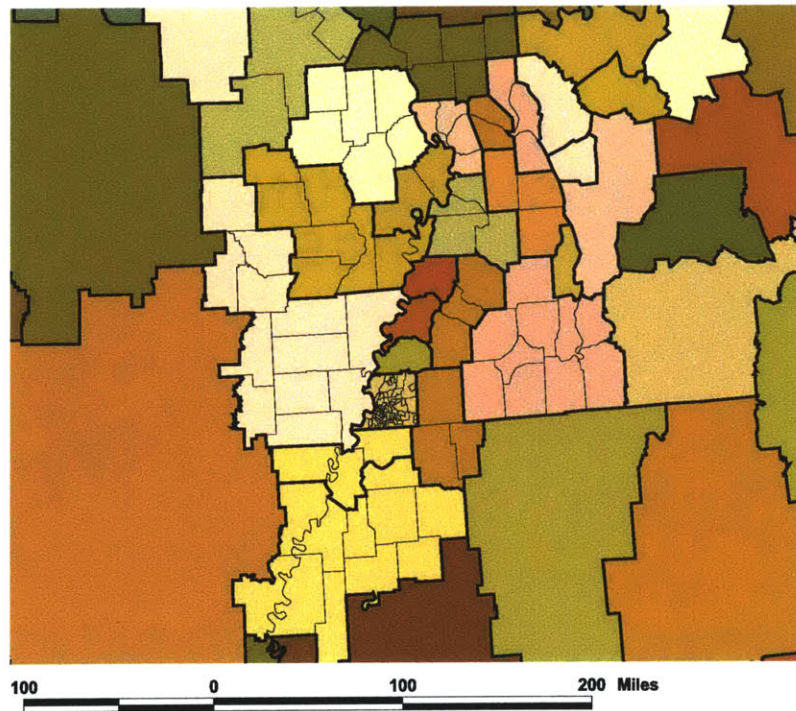


Figure 4-8: High resolution analysis regions

mation Systems (CGIS) website². Figure 4-9 shows the original network (low resolution) and Figure 4-10 shows the refined network. Figure 4-11 is a close-up of the refined network in Shelby County.

Bridges in the New Madrid region, which are extracted from the National Bridge Inventory (NBI) (Federal Highway Administration (FHWA) (1995)), are attached to the closest link in the refined network. The process is similar to that followed in assigning bridges to the links in the original network.

The refined network has about 860 nodes (highway intersections), 2600 links (highway segments), and 6000 bridges. This is roughly twice the number of nodes and links and three times the number of bridges in the original network.

Having obtained the refined models of the regions and the network, alternative strategies can be considered, such as refining the network alone or the regions alone,

²<http://www.cgis.gatech.edu>

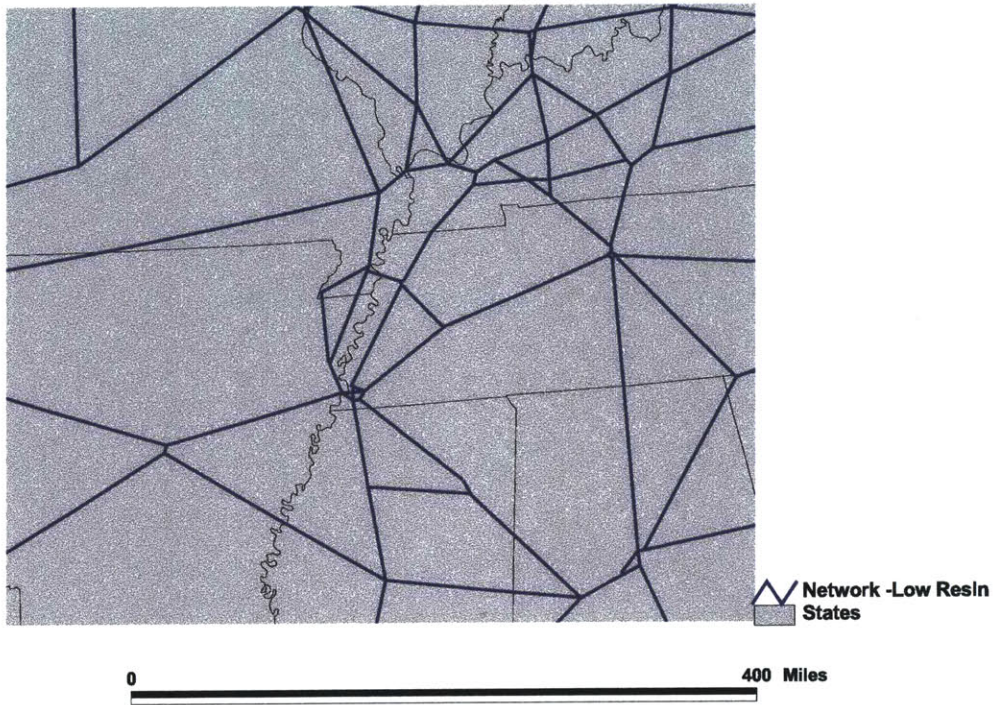


Figure 4-9: Low resolution network

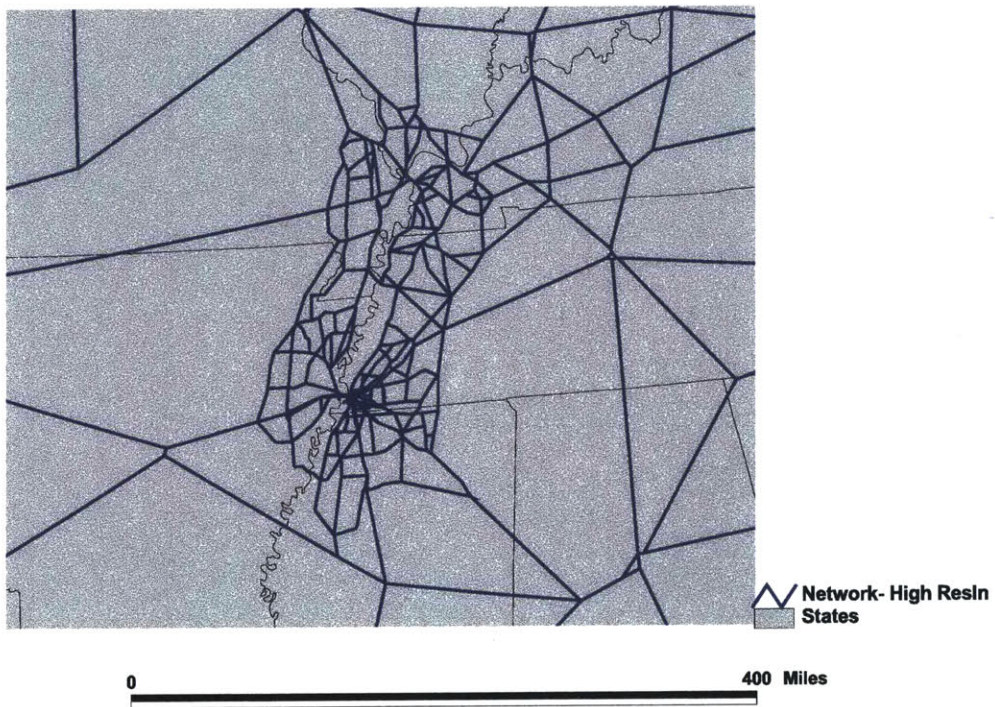


Figure 4-10: High resolution network

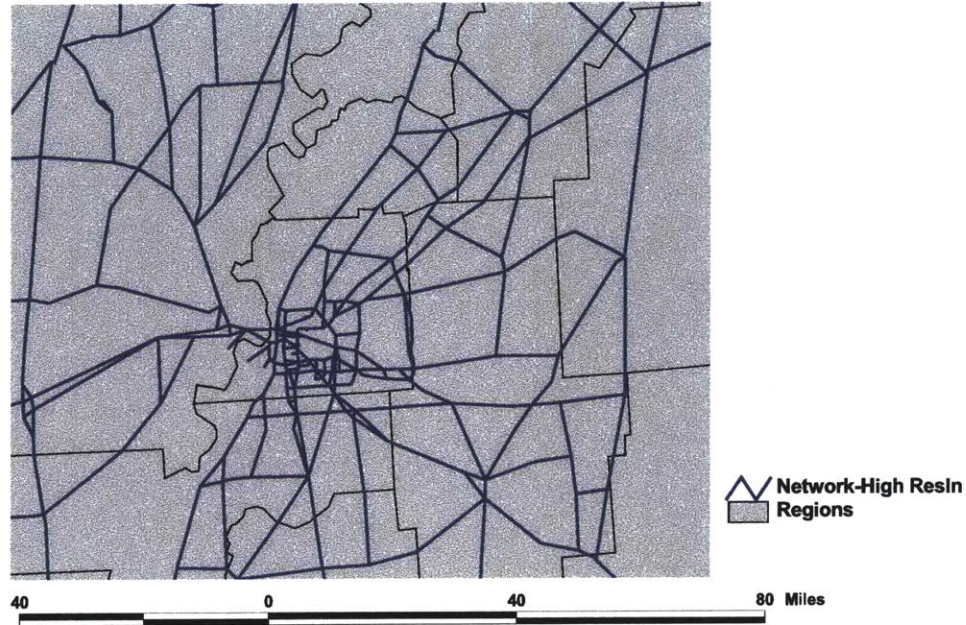


Figure 4-11: High resolution network: near Shelby County

or refining both the network and the regions. Figure 4-12 illustrates these alternative strategies. Figure 4-12(a) is a schematic representation of the low resolution model of the regions and the network. The regions are associated with the closest highway node to their centroid. The network alone can be refined while keeping the resolution of the regions fixed. This is illustrated in Figure 4-12(b). As a result, the network redundancy increases. Also, the highway nodes with which the regions are associated may change. Another strategy might be to refine the regions alone while keeping the network resolution fixed, which is shown in Figure 4-12(c). As a result, the spatial distribution of damage changes; some of the refined regions are more damaged and some less, compared to the average damage at the low resolution regions. Finally, both the regions and the network can be refined, as a result of which the spatial distribution of damage changes and the network redundancy increases. This is shown in Figure 4-12(d). The effects of these alternative strategies are discussed after presenting the results for the low resolution model of the regions and the network, which provide a basis for comparing the results from the refined models.

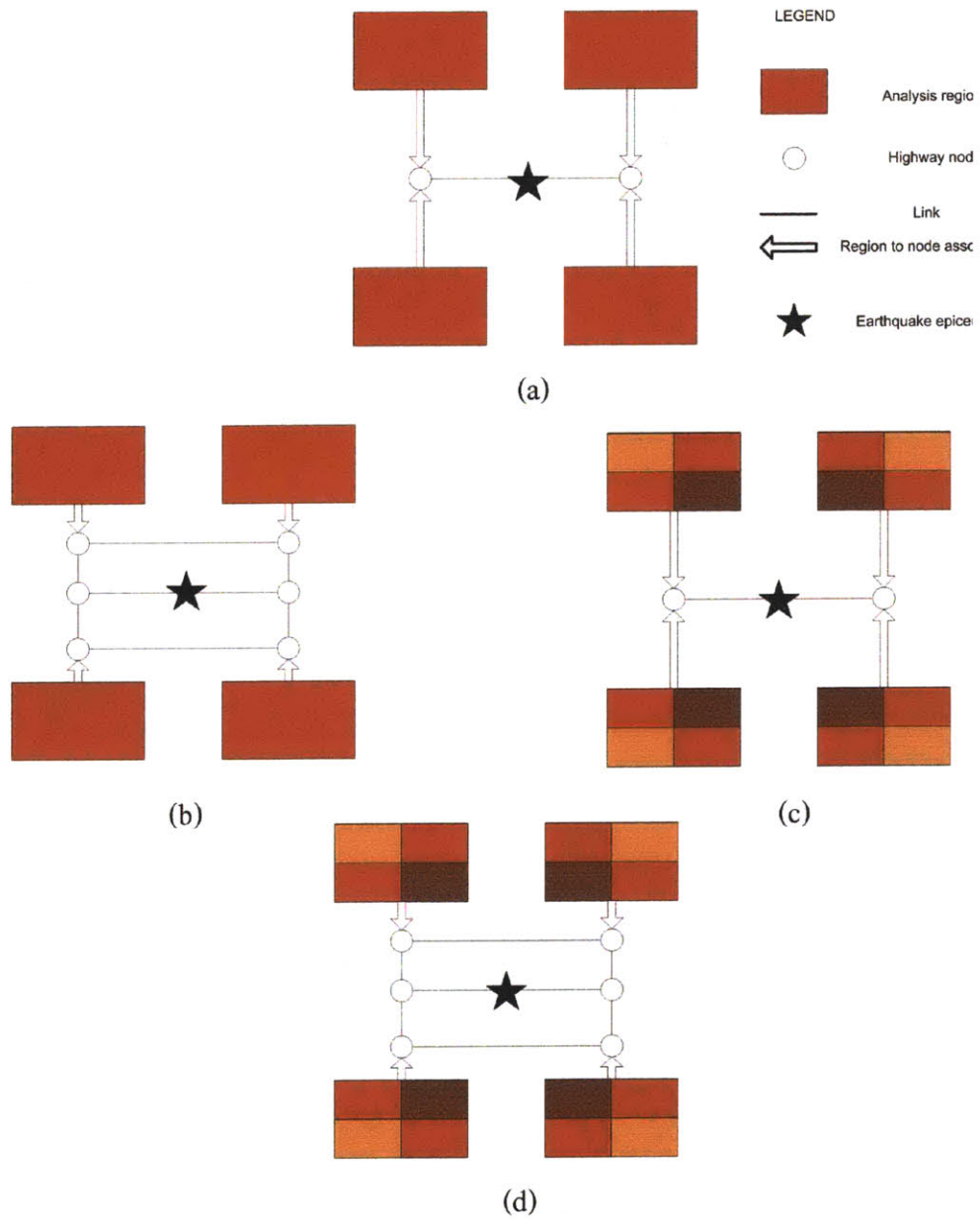


Figure 4-12: Schematic of alternative model resolutions (a) Low resolution regions and network (b) Low resolution regions, high resolution network, (c) High resolution regions, low resolution network (d) High resolution regions and network

4.2 Results - Low Resolution Model

This section discusses results obtained using the low resolution model of the analysis regions and the network. Scenario results are presented for a large earthquake of intensity 11.5MMI/ $8m_b$ (size measures used in the macroseismic and engineering approaches respectively) with epicentral coordinates (35.1 lat, -89.9 lon). This places the earthquake at the centroid of Shelby County. This is a rather pessimistic scenario as Shelby County is usually considered to be outside the most active New Madrid Seismic Zone (NMSZ). As the location of the epicenter coincides with the location of a large amount of property and economic activity, this could also be a possible worst-case scenario. Loss estimates³ using the macroseismic and engineering approaches are first presented. They are found to differ significantly. Reasons for the differences are then explained.

Macroseismic approach: The total direct economic losses are \$155.5B, of which a large fraction (75%) comes from building damage. The remaining direct losses are due to contents, pavement and bridge damage. The indirect economic losses due to reduced productions are \$25.7B and the indirect social losses due to reduced domestic consumptions (unmet domestic demand) are \$2.8B. Table 4.1 summarizes these results.

Figures 4-13 to 4-17 illustrate the initial damage and recovery of the non-durables manufacturing industry, which is one of the 13 economic sectors included in the model. Figure 4-13 shows the spatial distribution of initial damage. The image lacks perfect symmetry due to the irregular geometry of the analysis regions. Figures 4-14, 4-15, 4-16 and 4-17 show the functionality levels after 1 day, 1 week, 1 month and 6 months respectively. Immediately after the earthquake, the functionality is essentially 0 or 1, due to the highly non-linear damage-functionality relation (see Figure 3-9 for an example). However, more lightly damaged facilities recover faster and after 6 months most of economic sector is fully functional. Complete recovery takes about 1.5 years.

³All loss estimates in this chapter are in \$ B

	Loss (\$B)
Direct losses	
Building damage	114.4
Contents damage	40.1
Bridge damage	0.7
Link damage	0.3
Indirect losses	
Indirect economic losses	25.7
Indirect social losses	2.8

Table 4.1: Summary of losses from the macroseismic approach

Figure 4-18 shows the functionality of the pavements 1 day after the earthquake. The link functionality is based on the pavement functionality as well as the functionalities of the bridges on it. Bridges are typically more fragile and suffer greater loss of functionality than the pavements, and determine the link functionality. This is illustrated in Figure 4-19 which shows the link functionalities at Day 1. The link functionalities are reduced below the pavement functionalities in some cases. Figure 4-20 shows the link functionalities 1 month after the earthquake. In this case, most of the recovery takes place within 3 months. Complete recovery takes about 2.5 years. This is time needed to repair a few major bridges that are highly damaged.

Figure 4-21 shows the spatial distribution of the direct economic losses due to building damage. Lack of symmetry about the epicenter is due to uneven spatial distribution of property values. The direct losses due to building damage in a region depend not only on the damage ratio but also on the amount of building inventory present. Therefore, there may be greater losses in regions farther away from the epicenter than in nearby regions if the farther regions have more inventory than the nearby ones. Figure 4-22 shows the direct losses normalized by the value of inventory, which are more symmetrical about the epicenter. Figure 4-23 shows the contributions to the direct building losses from the various occupancy classes. The residential sector contributes the most to the direct losses. This is mainly because dwellings make up a large fraction of the building infrastructure value and to a lesser extent because the residential

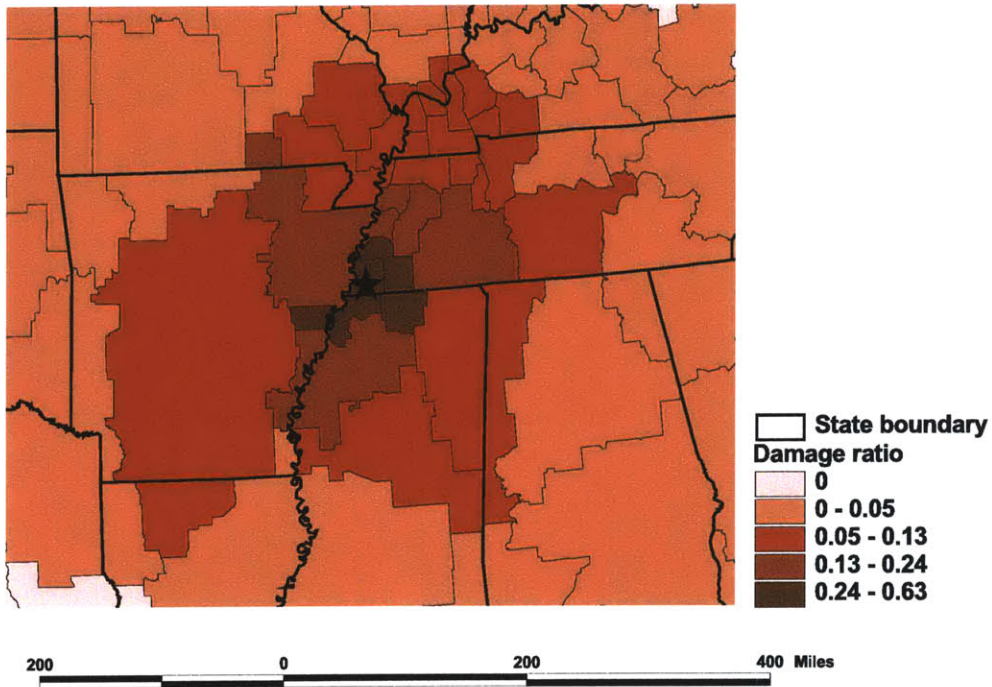


Figure 4-13: Damage to the non-durables manufacturing industry

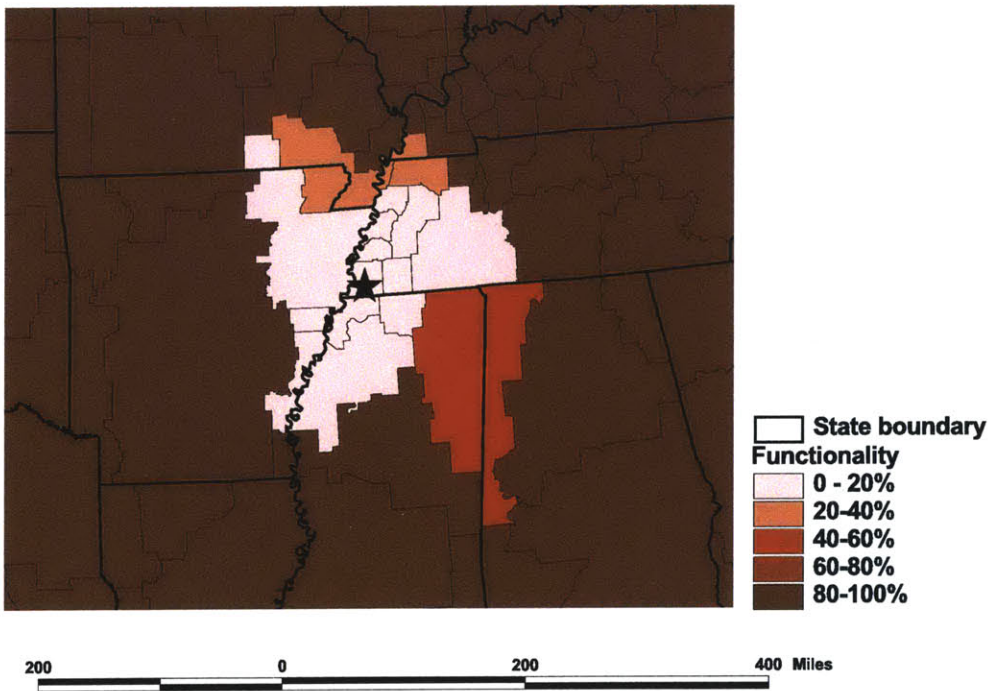


Figure 4-14: Functionality of non-durables manufacturing industry after 1 day

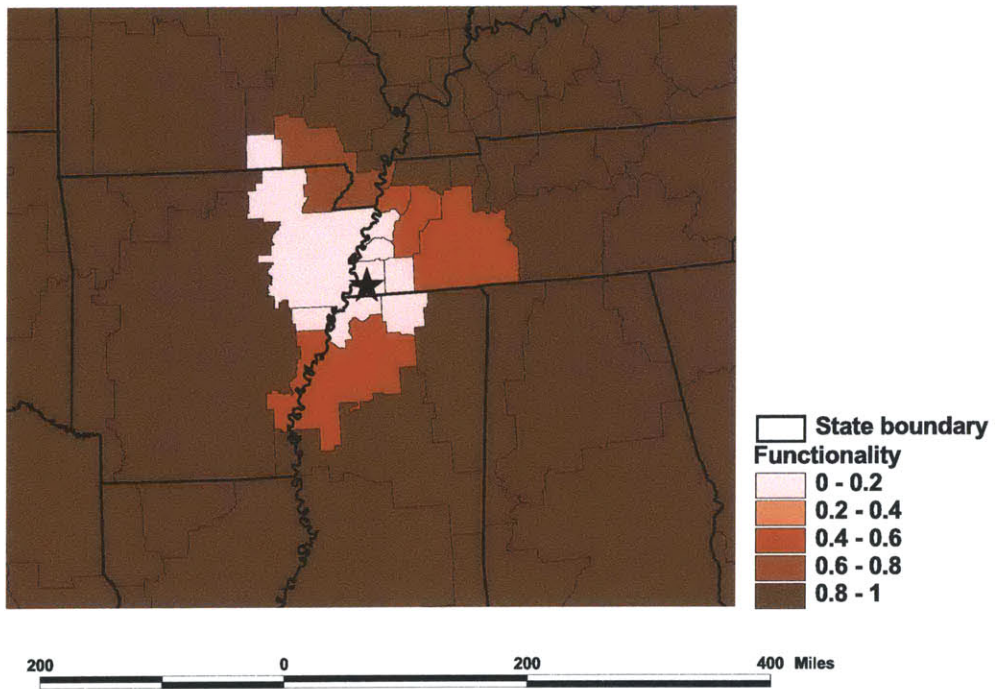


Figure 4-15: Functionality of non-durables manufacturing industry after 1 week

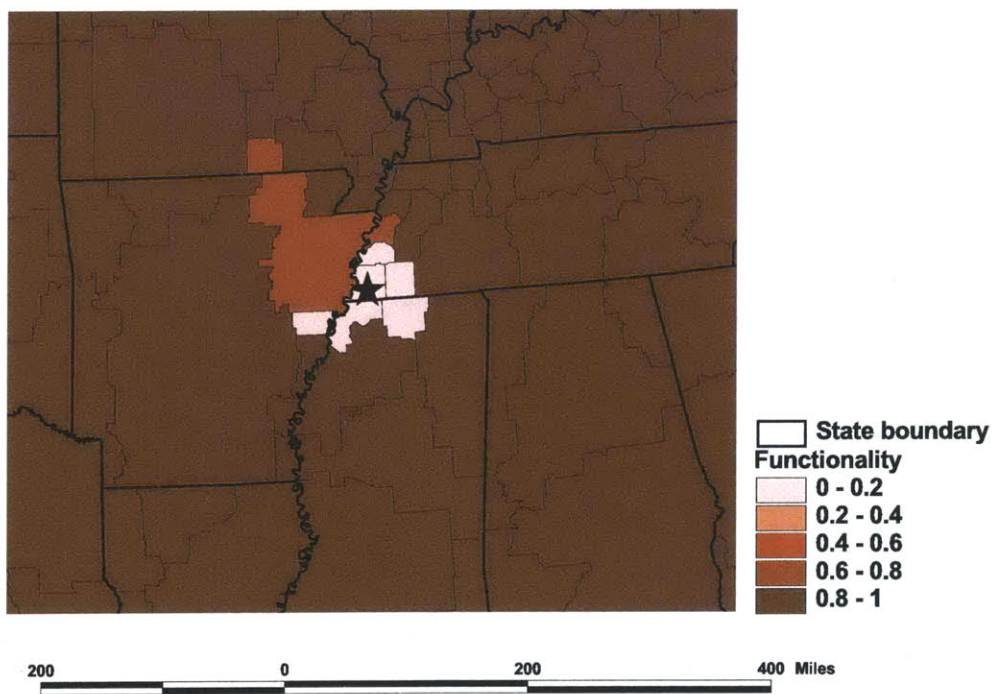


Figure 4-16: Functionality of non-durables manufacturing industry after 1 month

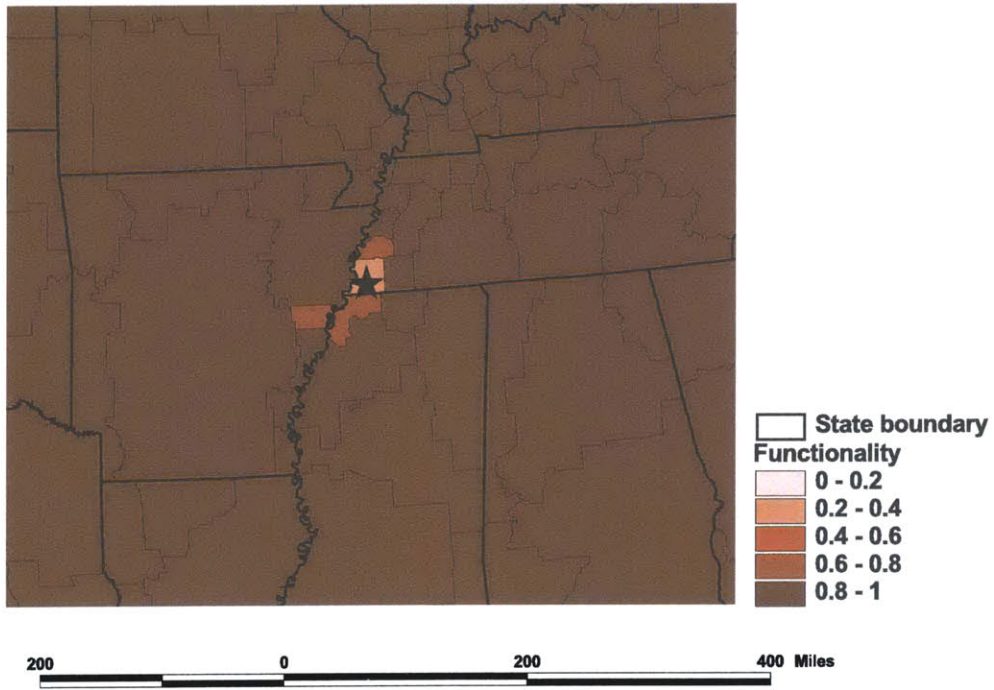


Figure 4-17: Functionality of non-durables manufacturing industry after 6 months

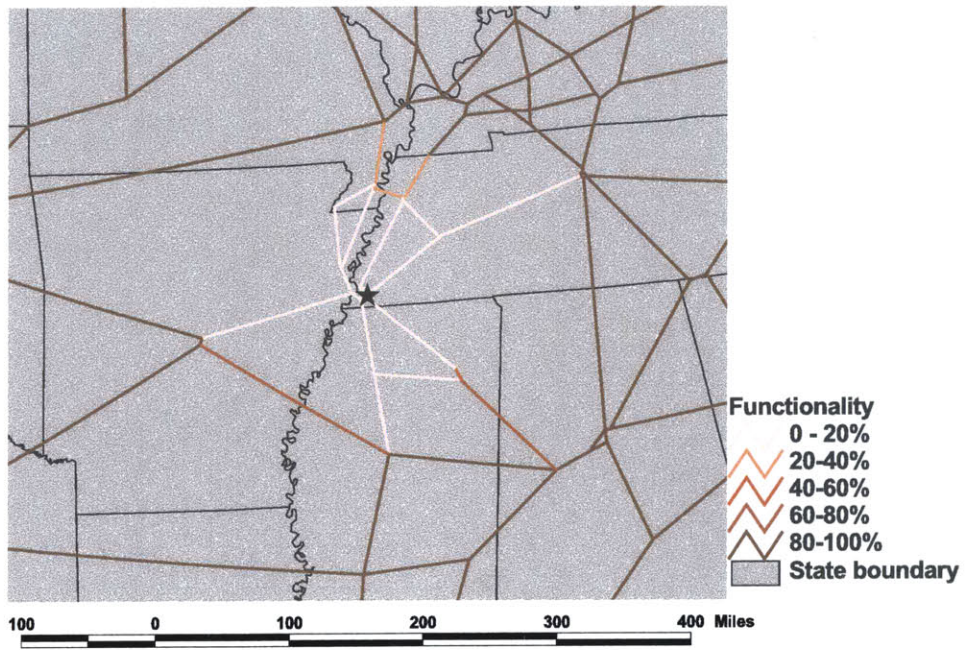


Figure 4-18: Pavement functionalities after 1 day

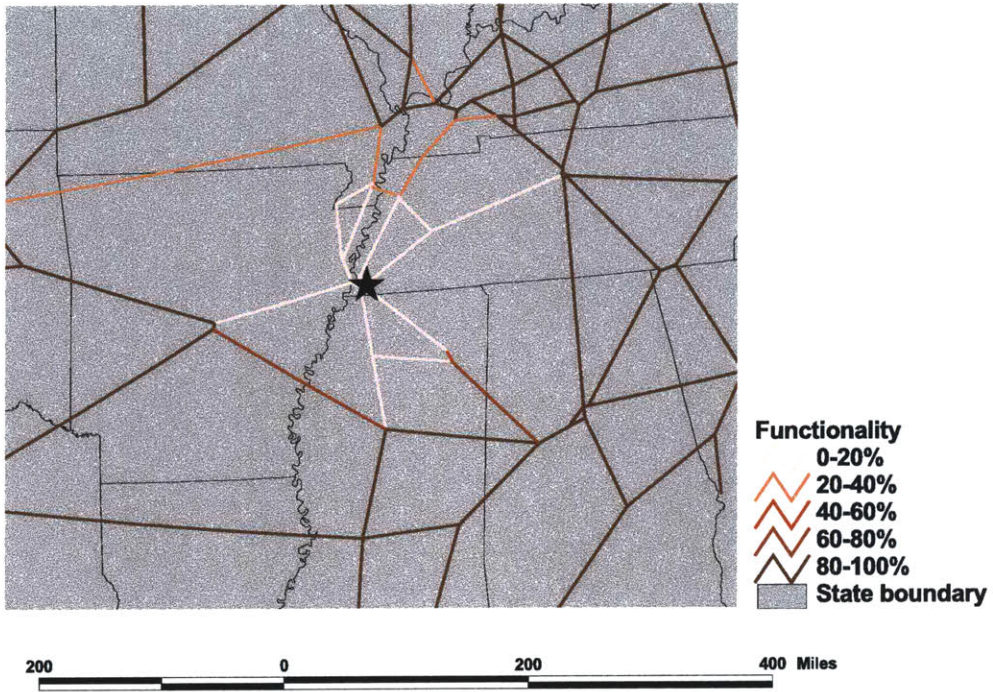


Figure 4-19: Link functionalities after 1 day

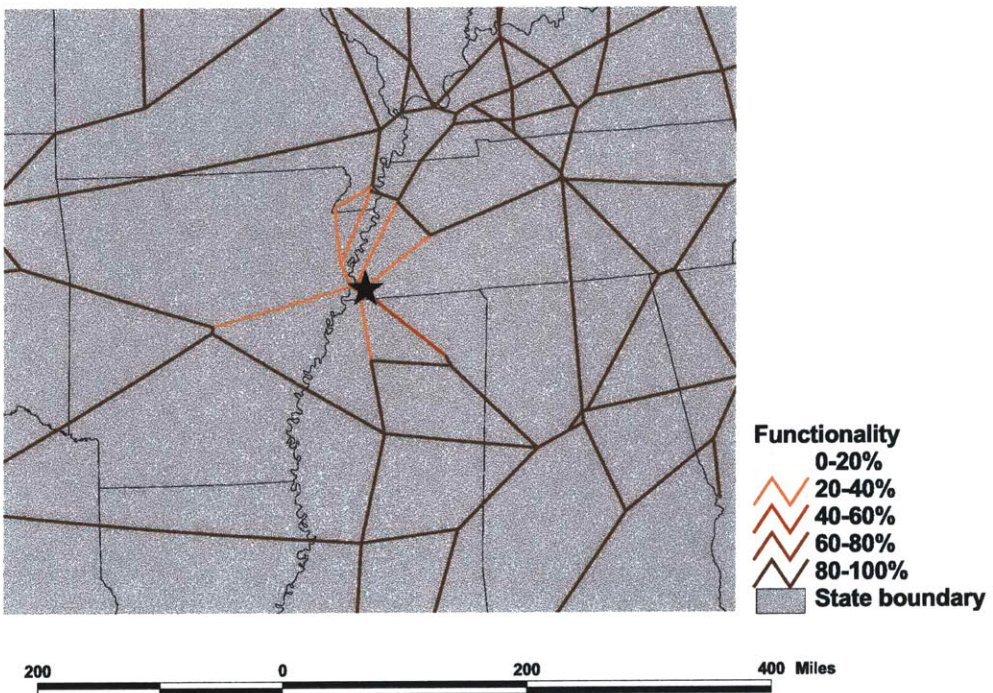


Figure 4-20: Link functionalities after 1 month

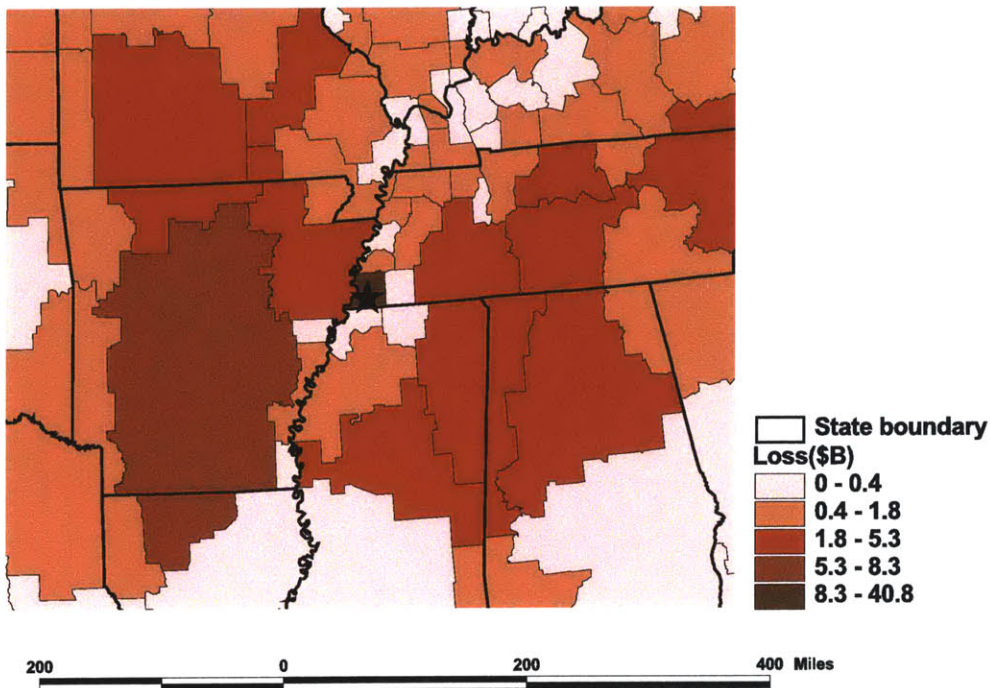


Figure 4-21: Spatial distribution of direct building losses

sector comprises a relatively large number of unreinforced masonry buildings, which have a high seismic vulnerability.

Figure 4-25 shows the evolution of the total indirect economic losses over time. The rate of increase of such losses is initially high, but tapers off as business recovers. Figure 4-24 shows the temporal evolution of losses from certain economic sectors normalized by the corresponding total losses. Agriculture, mining and construction are considered to be invulnerable to earthquakes and therefore do not suffer loss of functionality due to damage. The indirect losses from these sectors are very low and are entirely due to interactions with other sectors and disruption in commodity flows. Most of the losses from these sectors occur in the period when the network is severely disrupted. Other economic sectors suffer loss of functionality due to damage. The indirect losses from these sectors are much higher, as they are without any functionality for some period of time following the earthquake. Figure 4-26 shows the contributions to the indirect losses from the different economic sectors. The commercial/services

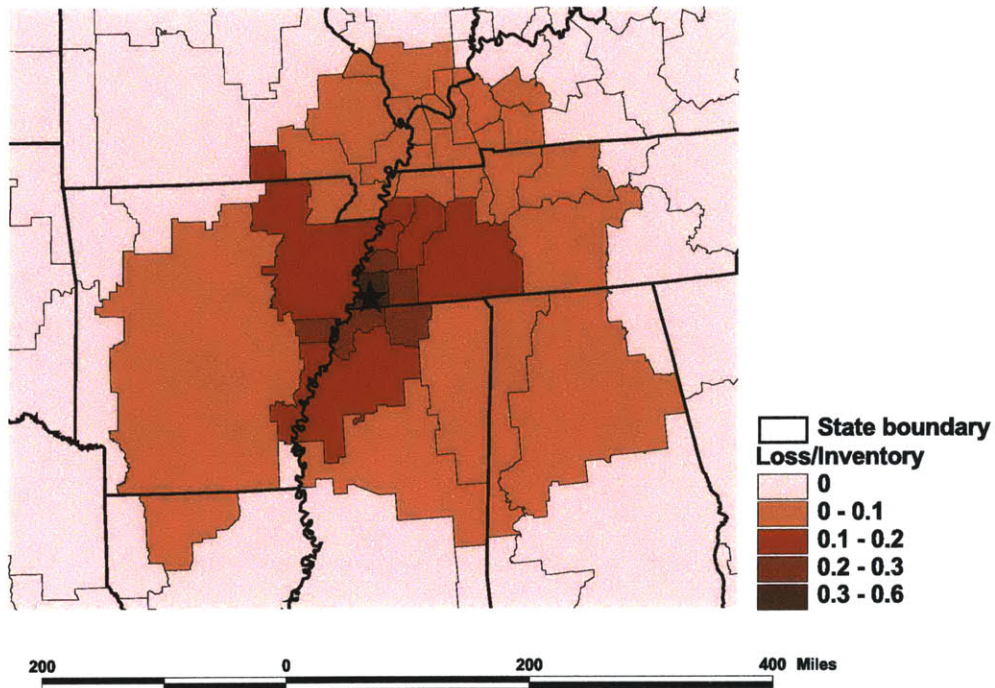


Figure 4-22: Spatial distribution of direct building losses normalized by inventory value

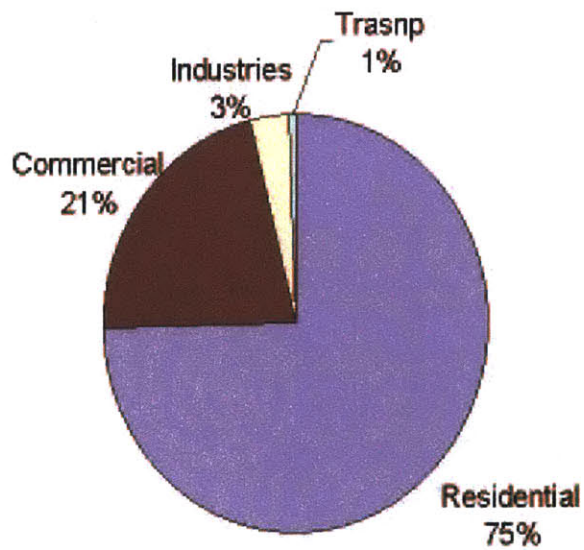


Figure 4-23: Direct building losses: contribution by occupancy class

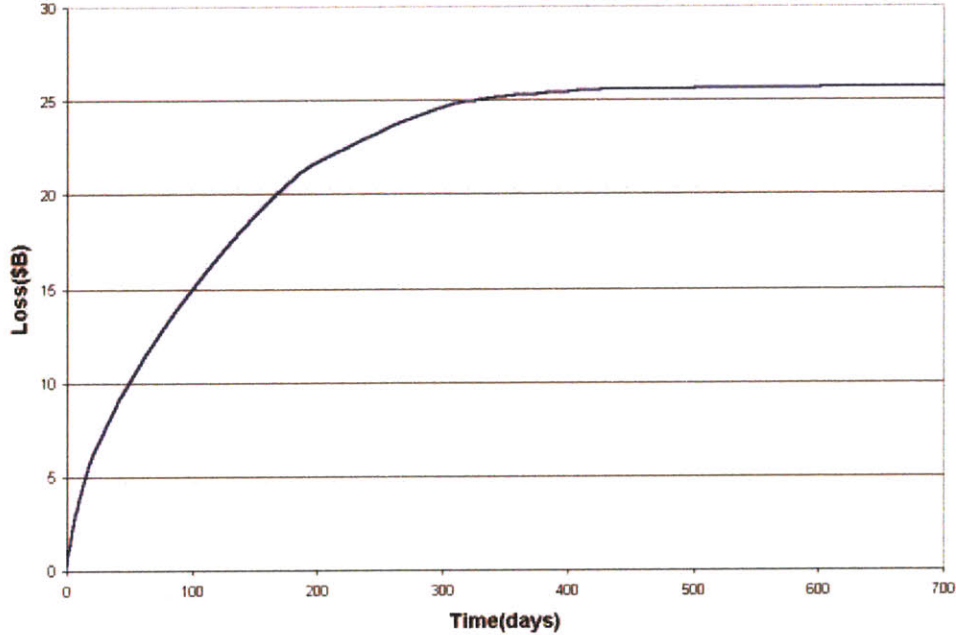


Figure 4-24: Evolution of total indirect losses over time

sector comprises most of the economic activity and therefore makes up most of the indirect losses. The spatial distribution of the indirect economic losses is shown in Figure 4-27, which reflects the geographical location of economic activities. Figure 4-28 shows the indirect economic losses normalized by total productions.

Engineering approach: The total direct economic losses are \$39.1B, of which \$35.3B comes from building damage. This is roughly a third of that obtained from the macroseismic approach (\$114.4B). The building losses are further disaggregated into structural losses (\$16.1B), non-structural drift sensitive losses (\$15.2B) and non-structural acceleration sensitive losses (\$4B). Although structural damage typically far exceeds non-structural damage, losses are comparable as non-structural components are assigned higher replacement costs. Figure 4-29 shows the spatial distribution of the losses due to building damage and Figure 4-30 shows losses normalized by inventory value. Compared to the corresponding figures from the macroseismic approach (Figures 4-21 and 4-22), a much

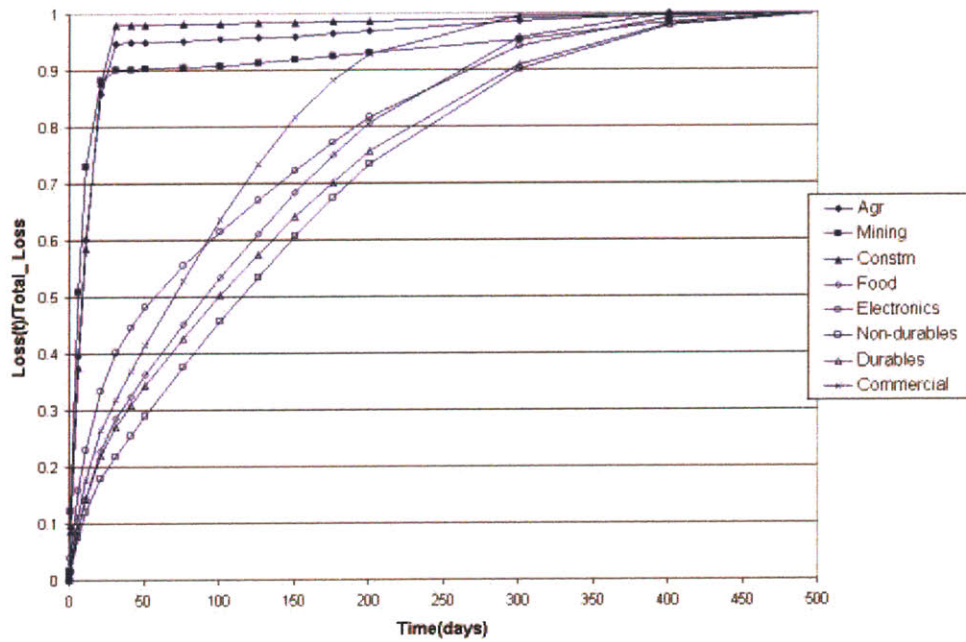


Figure 4-25: Evolution of indirect losses over time for certain sectors

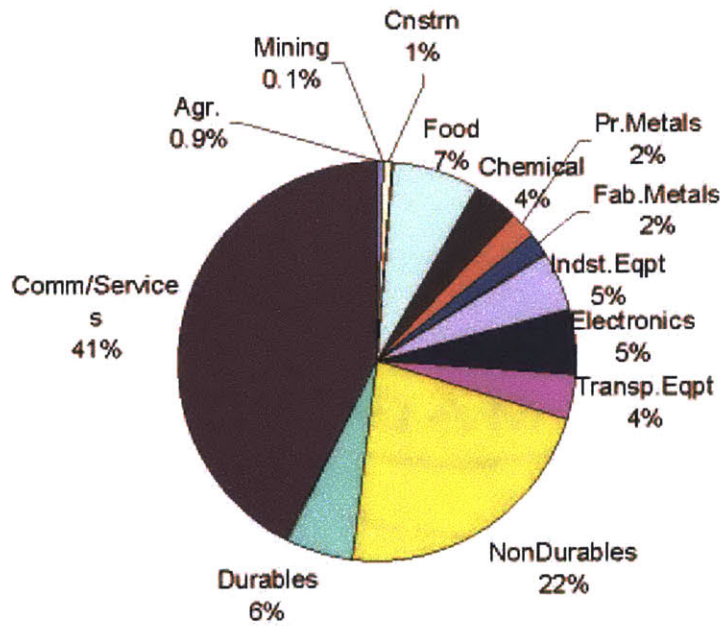


Figure 4-26: Indirect economic losses: contribution by economic sector

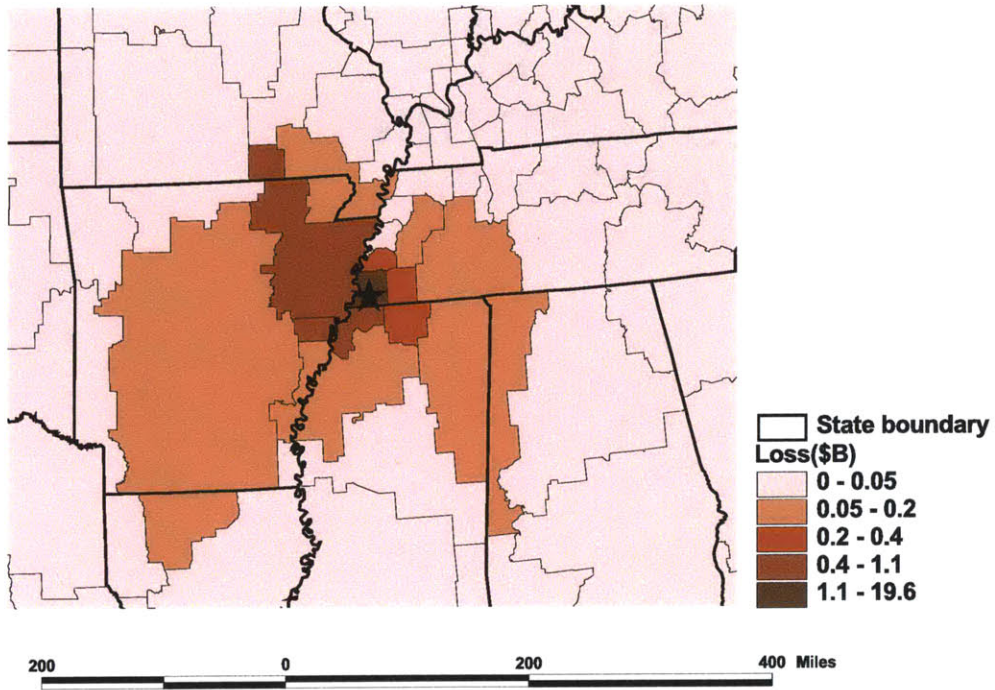


Figure 4-27: Spatial distribution of indirect economic losses

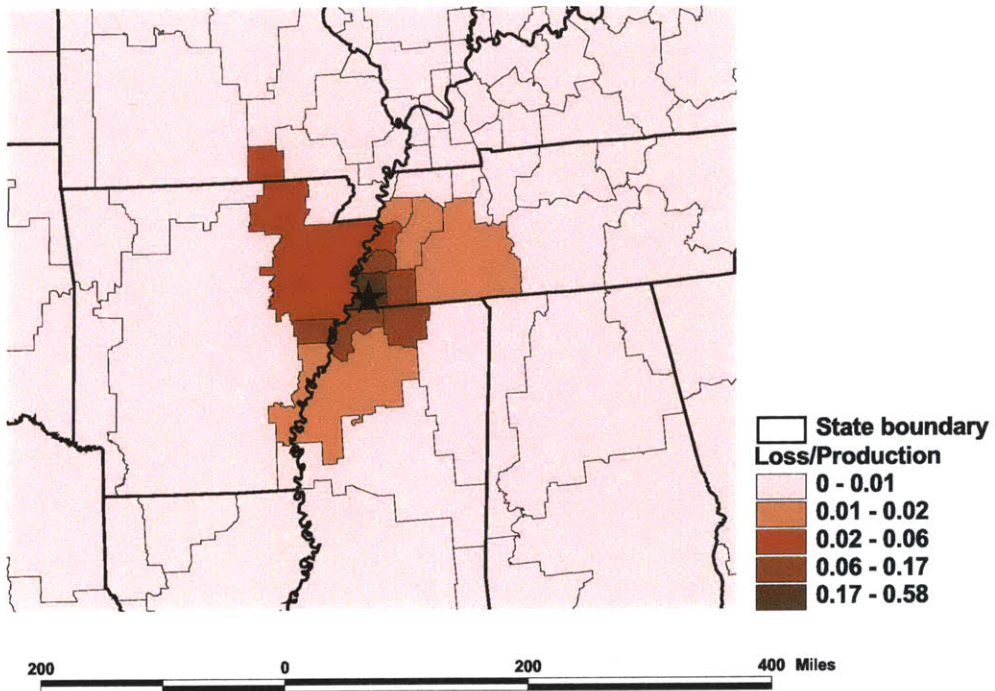


Figure 4-28: Spatial distribution of indirect economic losses normalized by production

	Engineering	Macro seismic
Direct losses		
Building damage	35.3	114.4
Contents damage	3.4	40.1
Bridge damage	0.3	0.7
Link damage	0.1	0.3
Fatalities	2300	Not implemented at this time
Indirect losses		
Indirect economic losses	33.9	25.7
Indirect social losses	1.8	2.8

Table 4.2: Comparison of losses: engineering approach vs macro seismic approach

smaller area is affected. This indicates differences in attenuation of ground motion intensity and estimated damage with distance in the two approaches. The contributions of the occupancy classes to the direct losses corresponds closely to the macro seismic results, with the residential sector accounting for the bulk of the losses.

The indirect economic losses are \$33.9B, which are higher than those from the macro seismic approach (\$25.7B). Figure 4-31 shows the spatial distribution of the indirect economic losses and Figure 4-32 shows them normalized by total production. The contributions to the indirect losses from the different economic sectors is similar to that in the macro seismic approach, with the commercial/services sector making up most of the losses.

Table 4.2 summarizes the losses from the engineering approach and also compares them to the corresponding macro seismic values. Reasons for differences in the loss estimates from the two approaches are given next.

Comparison of the loss estimates from the macro seismic and engineering approaches

- The most striking feature of Table 4.2 is that while the direct economic losses due to building damage from the engineering approach are much lower than the corresponding losses from the macro seismic approach, the indirect economic

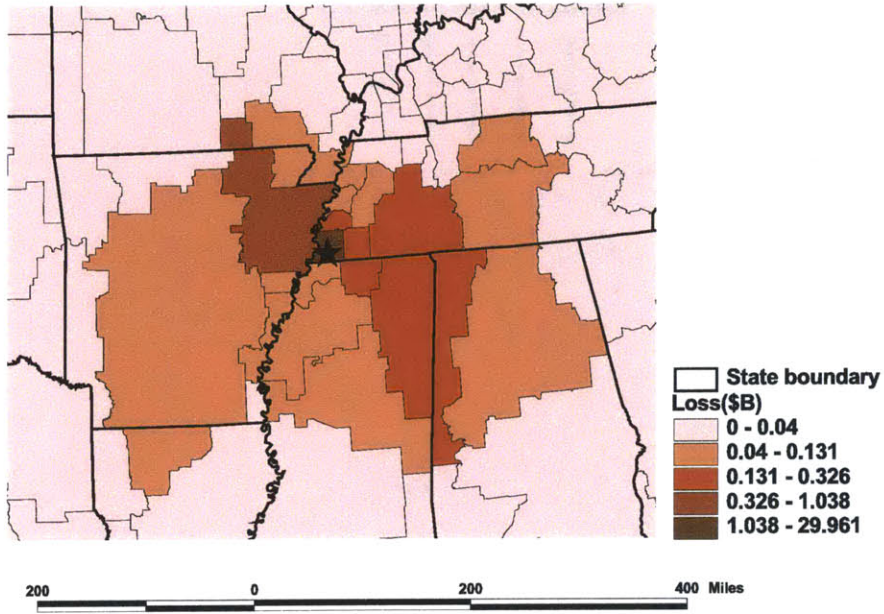


Figure 4-29: Engg. approach: spatial distribution of direct losses due to building damage

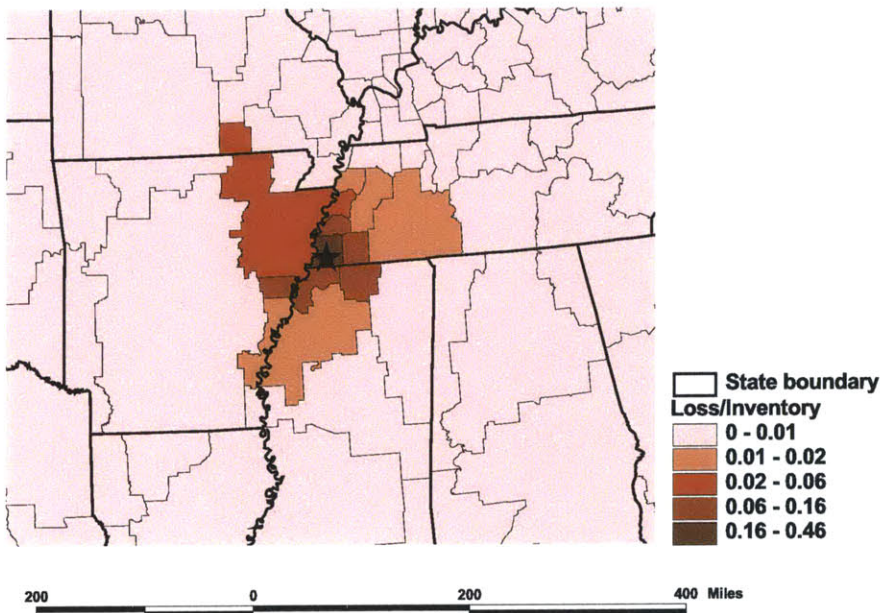


Figure 4-30: Engg. approach: spatial distribution of direct losses due to building damage normalized by inventory

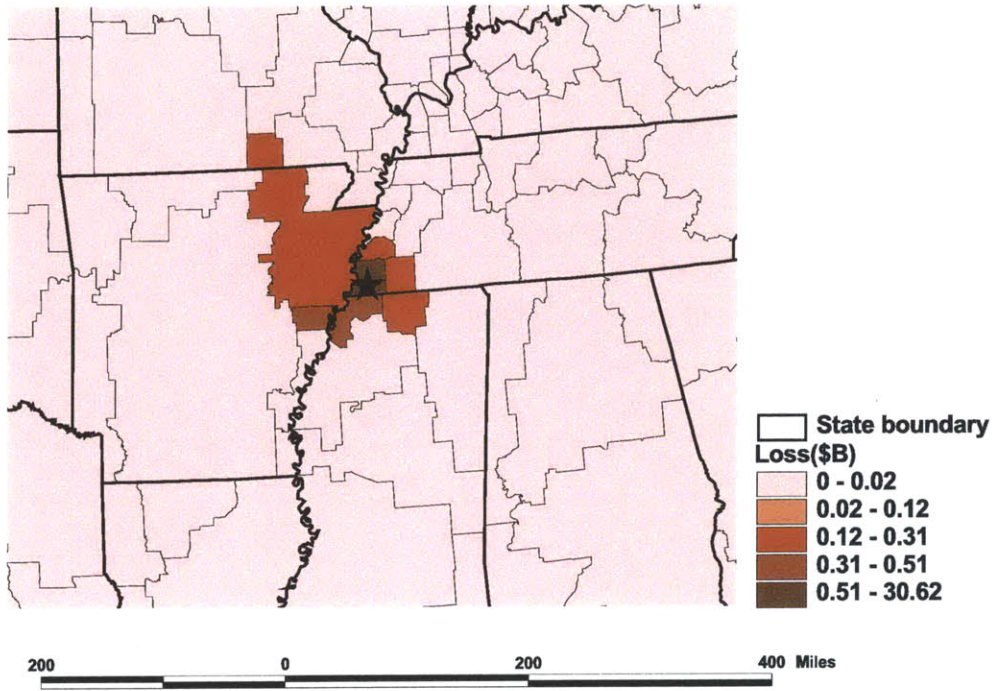


Figure 4-31: Engg. approach: spatial distribution of indirect economic losses

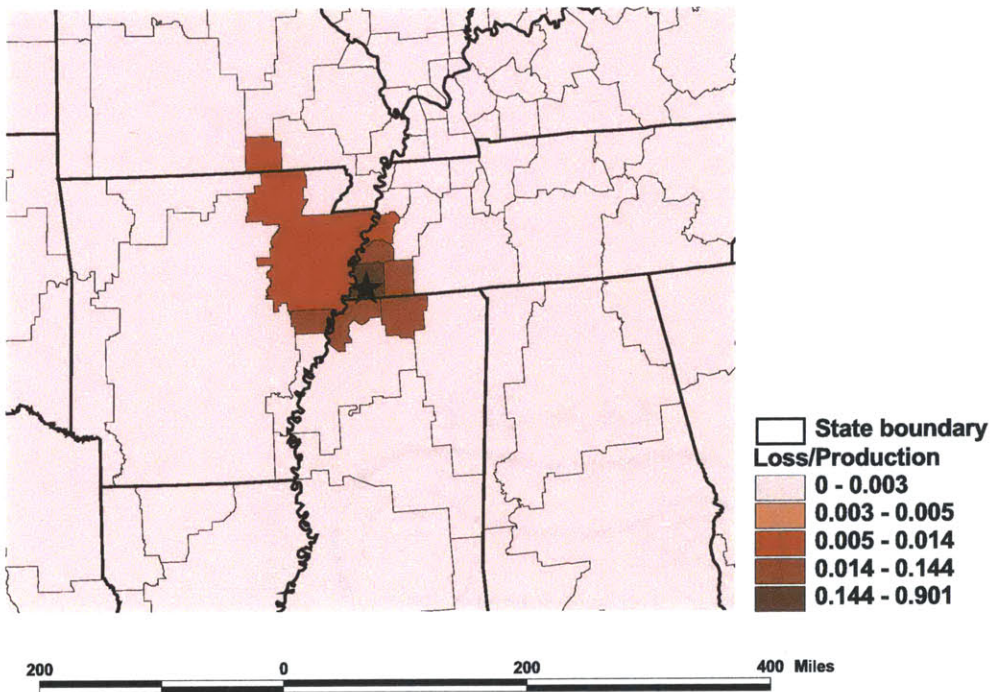


Figure 4-32: Engg. approach: spatial distribution of indirect economic losses normalized by production

losses are higher in the engineering approach compared to the macroseismic one. This is surprising since both direct and indirect economic losses are positively correlated with damage. In order to understand this difference in the relative magnitudes of the loss estimates from the two approaches, the direct and indirect losses are compared at various distances from the epicenter. Figure 4-33 compares the distribution of direct building losses with distance from the two approaches. The corresponding comparison for indirect losses is shown in Figure 4-34. Immediately one notices that while there is a large difference in the direct losses at distances $\geq 200\text{km}$ from the macroseismic and engineering approaches, the indirect losses from both approaches are the same ($\simeq 0$). The direct losses from the macroseismic approach far exceed those from the engineering approach beyond 200km. This is because of the slower attenuation of damage with distance in the two approaches (explained later). At 200km, the macroseismic approach predicts about 5% damage while there is essentially no damage in the engineering approach. Even though damage in the macroseismic approach is relatively low, the direct losses are very large because of the large amount of property in that distance range⁴. However, the indirect losses from the macroseismic approach are almost zero in the same distance range because of the non-linear damage functionality relation. There is a minimum damage level needed to cause a loss of functionality. The damage ratio in the macroseismic approach is below this threshold value and so there are no indirect losses.

We make two further comments on Figures 4-33 and 4-34:

- There are indirect losses at distances beyond 1000km while there are no direct losses there. There is no damage at that distance and so there are no direct losses. The indirect losses are due to economic inter-linkages between regions, as a result of which industries in far-off regions are affected by the disruption to the economy in the earthquake affected regions.

⁴Direct Loss = Damage ratio * Property Value

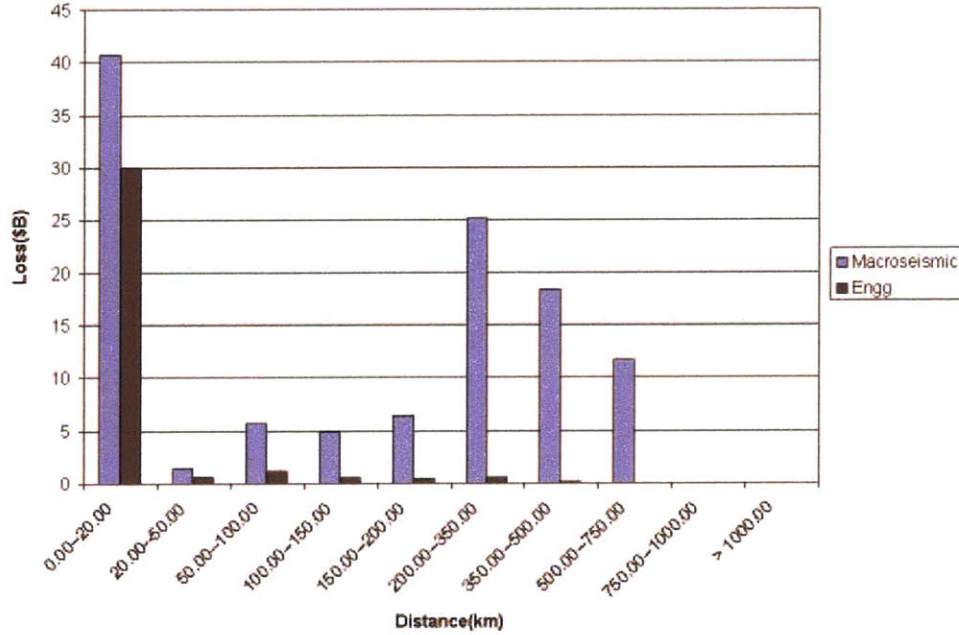


Figure 4-33: Distribution of direct losses with distance

- Within 20km from the epicenter, there are higher indirect losses from the engineering approach compared to the macro seismic approach, even though the corresponding direct building losses are lower. This is because of the different damage measures used to calculate the loss of functionality in the two approaches. As mentioned in Chapter 3, loss of functionality in the engineering approach is based on structural damage, while in the macro seismic approach it is based on the more aggregate building damage, which includes both structural and non-structural damage. Within 20km, structural damage in the engineering approach is greater than building damage in the macro seismic approach. Therefore, the indirect losses in the engineering approach are higher. However, since the structural components make up only a small fraction of the building value, the high structural damage is not completely reflected in the direct building losses from the engineering approach.

Comparison of attenuation of damage with distance in the two approaches: As

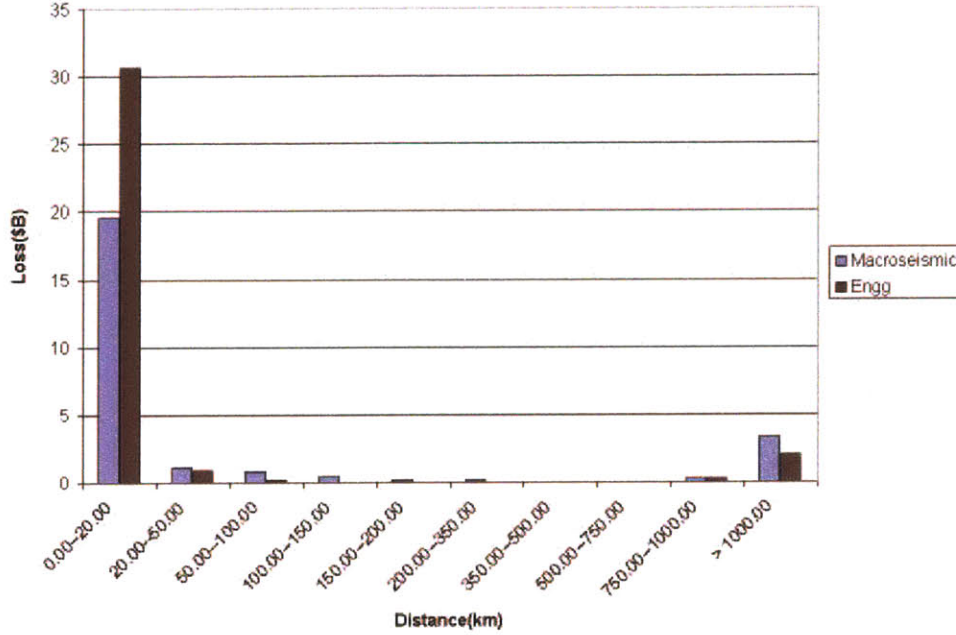


Figure 4-34: Distribution of indirect economic losses with distance

noted earlier, the difference in the direct losses from the two approaches is because of the difference in the rates at which damage decreases with distance. Figure 4-36 illustrates how damage⁵ to timber buildings varies with distance in the two approaches for an epicentral intensity of 11.5MMI/8m_b. In order to make this comparison, ground motion intensity is calculated at various distances using the attenuation relations (Bollinger (1977)/ Toro and Silva (2001)) and damage is obtained from intensity using the fragility relations (ATC-13 (1985)/ HAZUS (2000)). Figure 4-36 illustrates that damage attenuates more slowly in the macroseismic approach compared to the engineering approach. For example, at 100km, the macroseismic approach predicts about 10% damage, while the engineering approach predicts 0% damage irrespective of soil type. It is not immediately clear whether this difference results from differences in the attenuation relations or the fragility relations. Moreover, it is not possible to directly compare the attenuation and fragility relations used in the two

⁵Structural damage in case of the engineering approach

approaches as they are in different units - MMI (macroseismic) vs PGA/Sa/Sd (engineering).

In order to compare the attenuation relations, the intensity in MMI obtained from the Bollinger (1977) attenuation to PGA using the formula of Bernreuter (1981). This is compared to the PGA obtained from the Toro and Silva (2001) attenuation for different site conditions (hard rock (class A), very dense and soft rock (class C) and stiff soil (class D)). Figure 4-35 shows such a comparison for an epicentral intensity of $11.5\text{MMI}/8m_b$. Assuming that the Bernreuter (1981) conversion is a reasonable one, Figure 4-35 indicates that the Bollinger (1977) attenuation decays at a somewhat slower rate than the Toro and Silva (2001) relation, especially beyond 100km. This could account for some of the differences in the attenuation of damage in the two approaches. On the basis of this comparison, it also seems that the Bollinger (1977) attenuation gives the intensity for an average site in the New Madrid region, as it compares reasonably well with the Toro and Silva (2001) intensities for soil classes C and D, which are representative of the New Madrid soil types.

The fragility relations are not compared separately. However, based on the comparison of the attenuation relations, it seems that there must be differences in the fragility relations also. To illustrate this, consider the intensity at 100km. The intensities from the Bollinger (1977) agrees very well with that from Toro and Silva (2001) for soil class C, but the damages from the two approaches differ considerably. Therefore, the difference must come from the fragilities used in the two approaches - again assuming that the Bernreuter (1981) conversion accurately represents the relationship between MMI and PGA.

Understanding the reasons for the differences in the attenuation and fragility relations in the two approaches and resolving them is beyond the scope of this thesis. For the purposes of this thesis, the differences in the loss estimates from the two approaches are treated as resulting from uncertainties in the model parameters and modeling assumptions.

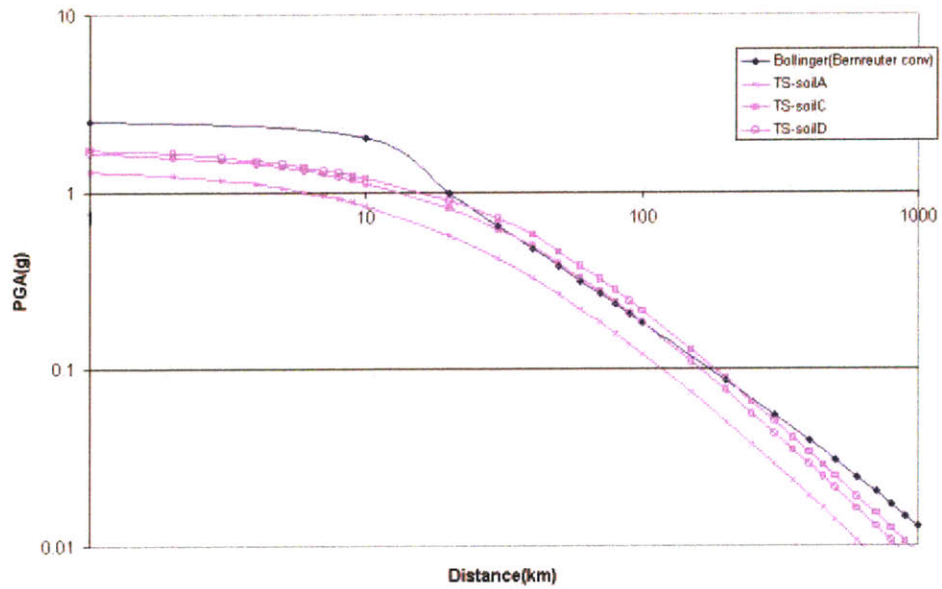


Figure 4-35: Comparison of attenuation relations: macroseismic vs engineering

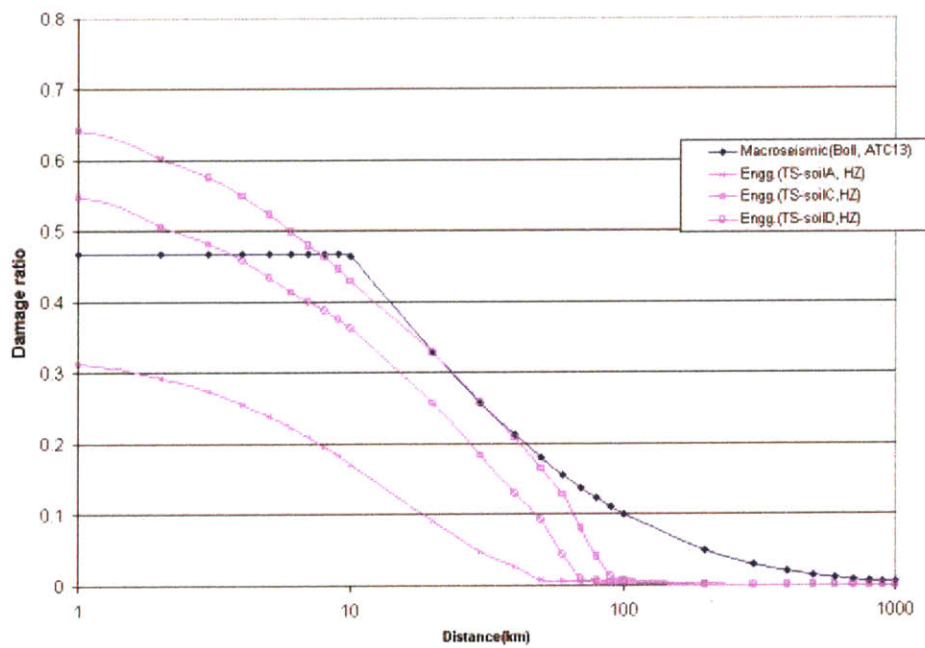


Figure 4-36: Comparison of attenuation of damage with distance for timber buildings: macroseismic vs engineering

- The decrease in the direct losses due to contents, pavement and bridge damage in the engineering approach relative to the macroseismic approach is again due to the faster attenuation of damage with distance in the engineering approach.
- The decrease in indirect social losses in the engineering approach compared to the macroseismic approach is mainly due to the lesser disruption in commodity flows, resulting from lower network damage. Lower network damage in the engineering approach is indicated by lower losses from pavement and bridge damage (see Table 4.2). As a result, more commodities can be sent into the earthquake affected regions. The additional commodities are mainly used to satisfy the domestic consumptions and this leads to a reduction in the indirect social losses. The additional commodity flows do not get significantly diverted towards the industries, as most industries in the earthquake affected regions are not operational and so do not have major demands.
- Increase in the transportation cost, defined as the ratio of the cost of routing the commodities on the damaged network to that of routing them on an undamaged network (described in Chapter 3), is also different in the two approaches. The macroseismic approach predicts a higher increase in the transportation cost (over a period of 60 days) than the engineering approach. Figure 4-37 shows the evolution of the transportation losses over time in both approaches and compares them with that predicted by Sohn et al. (2001b) for a similar New Madrid earthquake. Sohn et al. (2001b) predict a 0.6% increase in transportation costs over a period of 1 year. The loss is constant over time as Sohn et al. (2001b) do not model the recovery of the network and assume that the network remains in the initially damaged state. In contrast, this methodology models the recovery process and hence the transportation losses change over time. However, the change is not necessarily monotonic due to the differential recovery of the network and the economic sectors. The losses increase over time if the industries recover faster than the network (transportation demand exceeds capacity) and vice versa. The evolution of the transportation losses over time

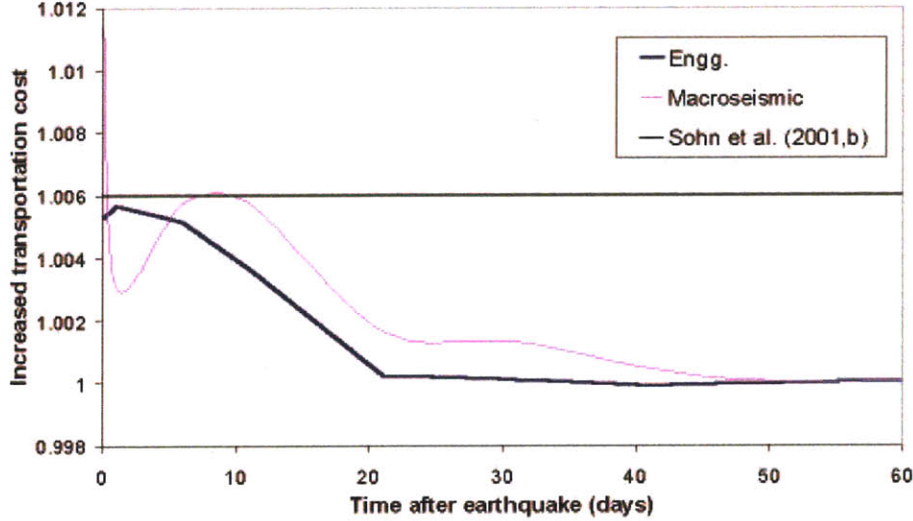


Figure 4-37: Increased transportation costs over time

is different in the macroseismic and engineering approaches. The macroseismic approach predicts a higher increase (1%) initially, which is due to the highly constrained nature of the network immediately after the earthquake. After 1 day, there is considerable network recovery, which results from the recovery of the lightly damaged links in the periphery. As a result, the transportation losses decrease at $t=1$ day. After that, industries begin to recover while the state of network does not change appreciably. Transportation demand goes up relative to capacity and so losses increase again. In the engineering approach, the transportation network is less severely damaged and recovers faster relative to the industries. Hence the transportation losses decrease more or less monotonically over time.

The results from increasing the model resolution are next discussed.

4.3 Results - High Resolution Model

This section looks at how the losses change when the resolution of the model is increased. The losses considered are the direct economic losses from building damage and the indirect economic and social losses. Contents losses are closely related to

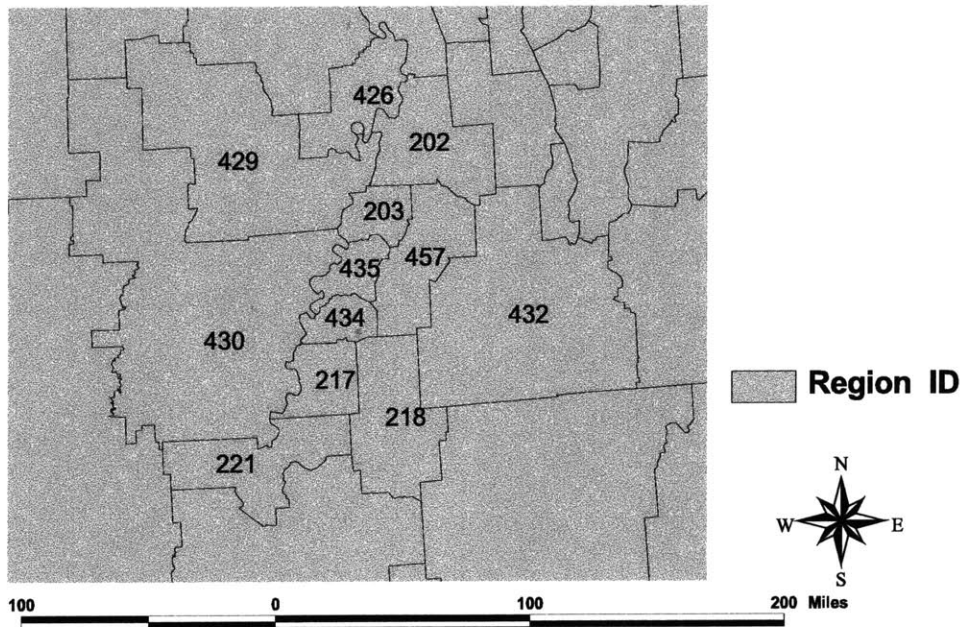


Figure 4-38: Region identification numbers

building losses while pavement and bridge losses form a very small fraction of the total losses. Hence changes in these losses are not specifically discussed. Effects of increasing the resolution of the network and the regions are separately examined first. Effects of increasing the resolution of both the network and the analysis regions are then considered. The losses are compared with those obtained from the low resolution model for alternative approaches (macroseismic vs engineering) and epicenter locations. These results provide a sense of the importance of increasing the model resolution, on the basis of which suggestions are made as to the spatial discretization and network resolution needed to obtain reasonably accurate loss estimates.

In the following discussions, regions are referred to by their id's, which are unique numbers assigned to them. Figure 4-38 shows the id's of certain regions (low resolution regions) within about 200km from the epicenter.

4.3.1 Effects of increasing the resolution of the transportation network

The resolution of the transportation network is increased (high resolution network) while keeping the resolution of the analysis regions unchanged (low resolution regions). This is done by associating each low resolution region with the highway node of the refined network closest to its centroid. Results are compared with those obtained using low resolution model of the network and the regions for a 11.5MMI earthquake in Shelby County (35.1 lat, -89.9 lon). The modeling approach used in the macroseismic one. Figure 4-39 shows the low resolution model of the regions and the network and Figure 4-40 shows the case when the network is made more detailed while the resolution of the regions is unchanged.

Table 4.3 lists the change in the losses from increasing the network detail. Direct losses due to building damage do not depend on the resolution of the network and so are unchanged. The indirect losses are affected, primarily due to changes in the commodity flows on the refined network relative to the original network and also because of changes in the highway nodes with which the regions are associated in the two networks (as explained earlier in Section 4.1). Figure 4-41 shows the changes⁶ in the indirect economic and social losses for regions within the area of increased network resolution (roughly within 200km of the epicenter). While most regions experience a decrease in the losses, there are some regions (435, 202) where the losses increase. These regions (435,202) are associated with less damaged highway nodes in the original network compared to the refined network (shown in Figures 4-2 and 4-3).

The social losses are more sensitive to increasing the network resolution than the economic losses. This is because most industries in the regions where the network resolution is increased are not operational due to earthquake damage. As a result, they are unaffected by the additional commodity flow capacity of the refined network. In fact, only 30% (\$0.5B) of the total decrease in the indirect economic losses comes from regions where the network resolution is increased. On the other hand, there is a

⁶Losses when the network is refined less the losses when the low resolution network is used

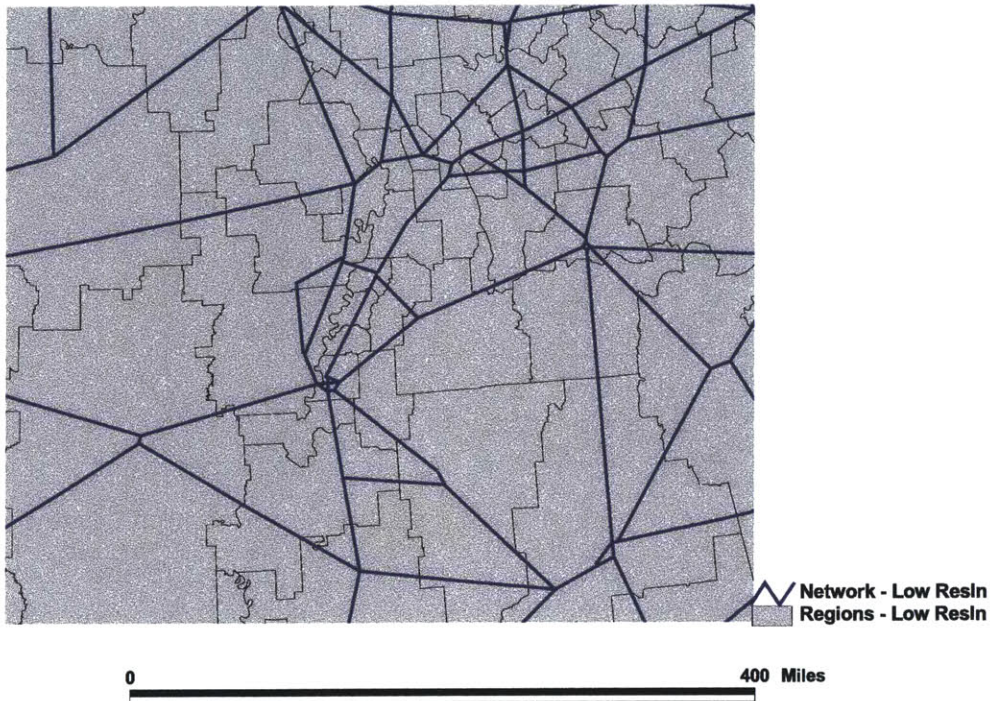


Figure 4-39: Low resolution model of the regions and the network

	Low resolution network Low resolution regions	High resolution network Low resolution regions
Building losses	114.4	114.4
Indirect economic losses	25.7	24.2
Indirect social losses	2.8	1.8

Table 4.3: Summary of losses: effects of increasing the network resolution

substantial decrease in the social losses (\$0.95B) from these regions, as in the absence of industrial demand the additional flow capacity is used to satisfy the domestic demand. Industries in regions where the network resolution is not increased (beyond 200km of the epicenter) also benefit from the additional flows, since they get more of their required net exports and imports. As a result, there is a reduction in the economic losses from the farther regions and this accounts for the remaining 70% (\$1B) of the total decrease in the economic losses.

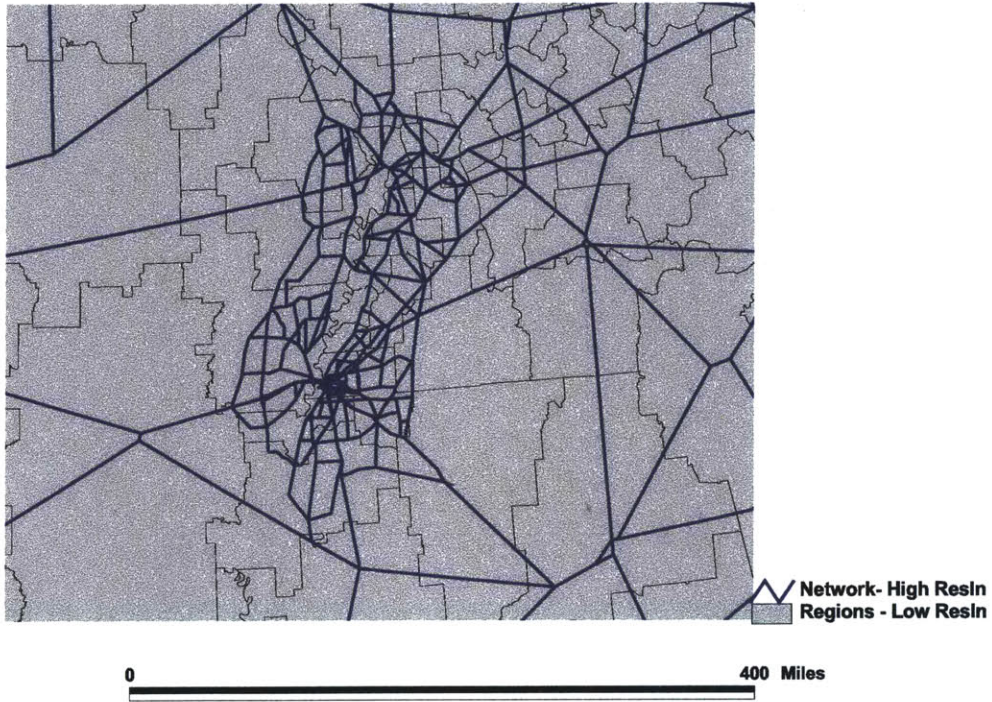


Figure 4-40: Low resolution regions, high resolution network

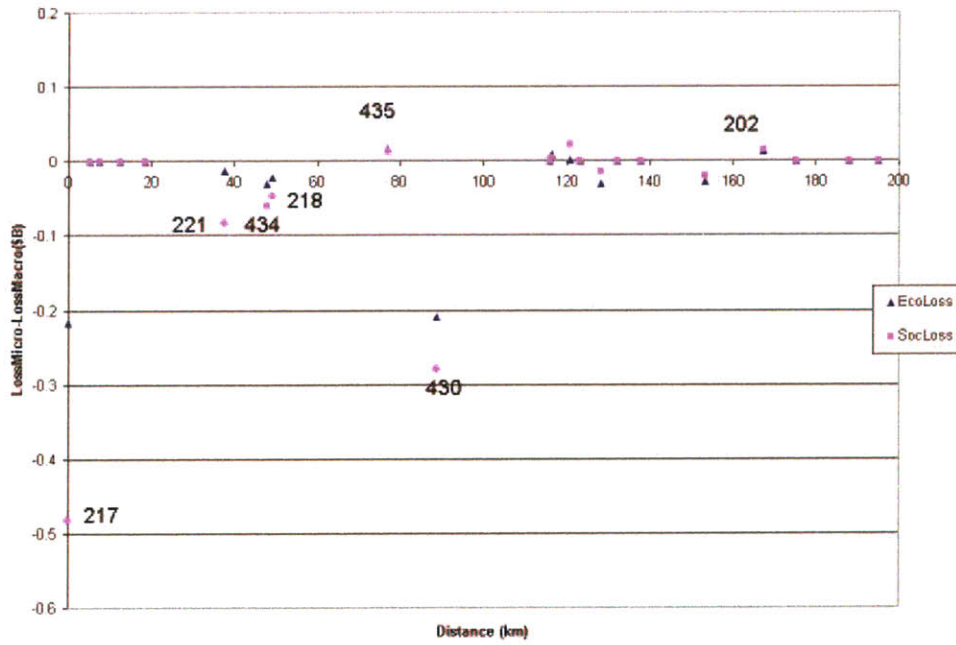


Figure 4-41: Change in the indirect losses from refining the network

4.3.2 Effects of increasing the resolution of the analysis regions

The resolution of the analysis regions is increased while keeping the resolution of the transportation network unchanged. This is done by associating each high resolution region with the highway node of the low resolution network closest to its centroid. Results are compared with those obtained using the low resolution models of the regions and the network for the same 11.5MMI earthquake located at the centroid of Shelby County (35.1 lat, -89.9 lon). The modeling approach used is the macroseismic one. Figure 4-39 shows the low resolution model of the regions and the network and Figure 4-42 shows the case when the regions are refined while the network resolution is unchanged.

Table 4.4 gives the change in the losses from increasing the resolution of the regions. The effects of having a finer spatial discretization are more local (i.e., within the area of increased resolution) compared to when the network resolution is increased. This is because the network capacity/redundancy does not change in this case and so the effects do not propagate throughout the system. The direct and indirect losses are affected by modeling the spatial distribution of property within the regions⁷ due to the non-linear damage-distance relation (as explained in Section 4.1). There is greater change in the indirect economic losses compared to when the network is made more detailed (\$2.5B vs \$1.5B). Most of it (85%, \$2.1B) comes from the regions which are made more refined. The social losses from these regions also decrease due to the higher industrial productions there. However, they do not decrease as much as when the network is refined (\$0.5B vs \$1B). This is because only a part of the increased industrial productions are used to meet the domestic demand; the rest is used to satisfy the industrial demand.

A more detailed comparison, at the level of the low resolution analysis regions, is made in Figure 4-43. Here the losses from the refined regions are aggregated

⁷original, low resolution regions

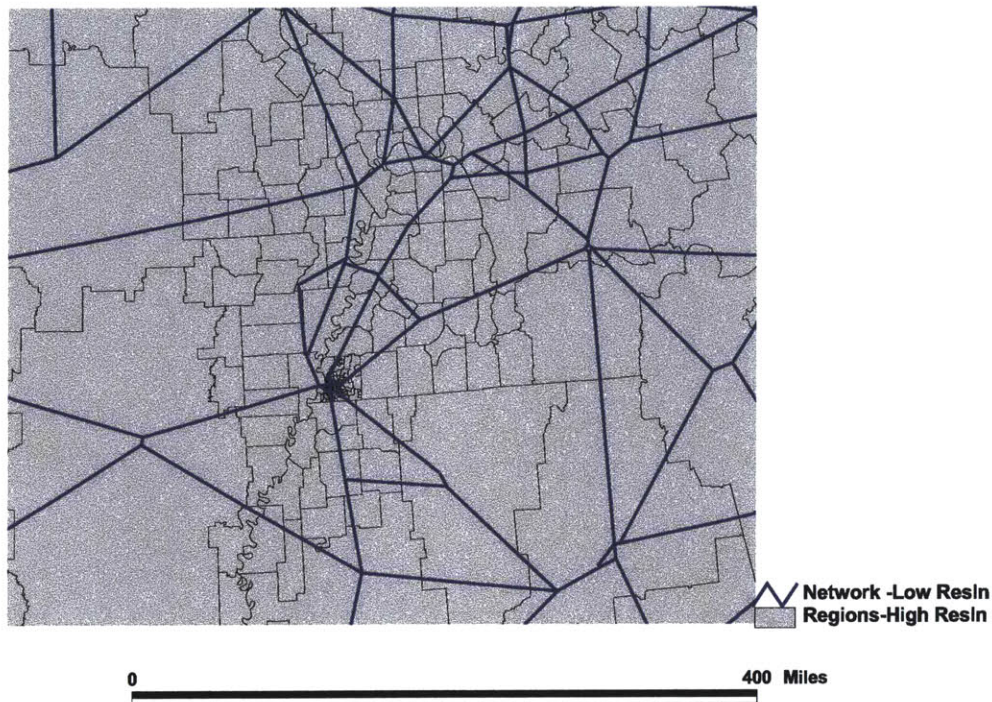


Figure 4-42: High resolution regions, low resolution network

to the “parent” regions⁸ and are then compared with the corresponding losses from the same regions in the low resolution model. The loss ratio depends on the spatial distribution of property within each low resolution region relative to its centroid. In Shelby County (region 217), the losses are lower when the spatial distribution of properties within it is considered. This is because in the low resolution model, all properties in this county are moved to the centroid, which is also assumed to be the epicentral location. In contrast, losses from region 430 decrease. This is due to the non-linearity in the damage-distance relation and the uneven spatial distribution of property in the region - a large fraction of the region’s property is located closer to the epicenter than its centroid. Finally, there are regions where the location of property is reasonably represented by their centroids, such as region 221. The losses from such regions do not change significantly on refining them.

⁸The low resolution analysis region which is decomposed to yield the given high resolution regions

	Low resolution network Low resolution regions	High resolution network High resolution regions
Building losses	114.4	112.8
Indirect economic losses	25.7	23.2
Indirect social losses	2.8	2.3

Table 4.4: Summary of losses: effects of refining the analysis regions

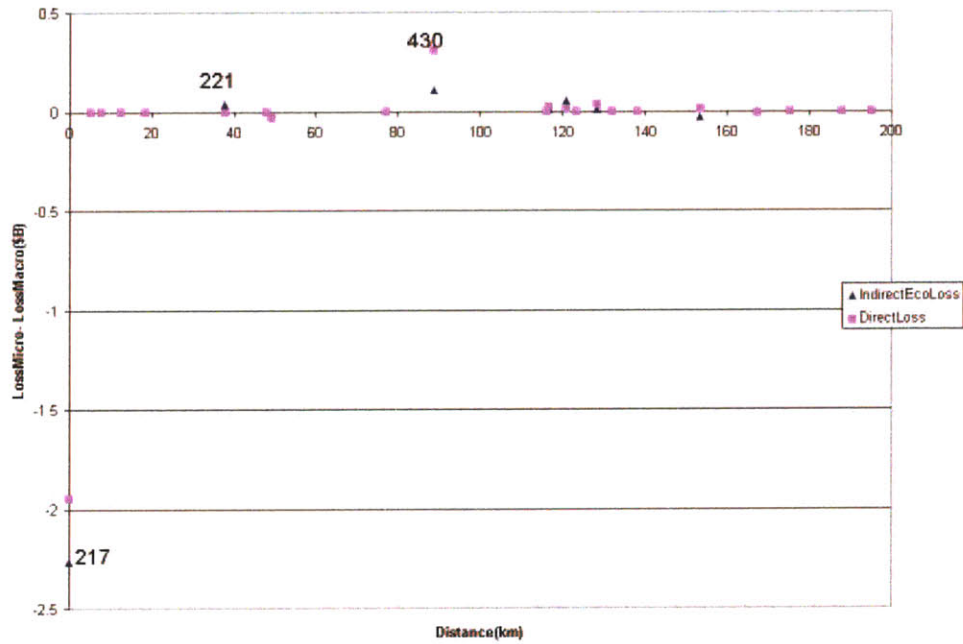


Figure 4-43: Change in losses from refining the analysis regions

Scenario 1 - Macroseismic	Low resolution network Low resolution regions	High resolution network High resolution regions
Building losses	114.4	112.8
Indirect economic losses	25.7	22.1
Indirect social losses	2.8	1.6

Table 4.5: Summary of losses: macroseismic approach, Scenario 1

4.3.3 Effects of increasing the resolution of the regions and the network

Refining both the analysis regions and the network combines the effects of refining each separately. The change in the direct losses is the same as when the regions alone are refined. The change in the indirect losses is roughly the sum of the changes from refining the regions and the network separately. This is shown in Table 4.5, which gives the losses from increasing the resolution of the network and the regions for the 11.5MMI scenario earthquake in Shelby County. Figure 4-44 shows the difference in the direct and indirect economic losses from the high and low resolution models. Regions 217 and 430 show the largest sensitivity to the spatial discretization/network resolution, for reasons that have been explained earlier. The above results have been obtained using the macroseismic approach. The losses from the low and high resolution models are next compared using the engineering approach.

Table 4.6 compares the losses from the low and high resolution model using the engineering approach for an $8m_b$ earthquake at the centroid of Shelby County. In this case, there is a very large sensitivity of the losses to the resolution of the model. The greatest sensitivity is at Shelby County, where the losses decrease dramatically - by \$14B and \$18B in the direct and indirect losses respectively. This is due to the rapid attenuation of damage with distance in the engineering approach. Figure 4-45 shows the difference in the losses in regions excluding Shelby County (region 217), where the differences are not very large.

The effect of earthquake location on the resolution of the model is examined by considering a scenario earthquake, referred to as “Scenario 2”, where the epicenter is located north of Shelby County (361. lat, -89.6 lon); see Figure 4-46. The main dif-

Scenario 1 - Engg.	Low resolution network Low resolution regions	High resolution network High resolution regions
Building losses	35.3	20.9
Indirect economic losses	33.9	14.8
Indirect social losses	1.8	1.1

Table 4.6: Summary of losses: engineering approach, Scenario 1

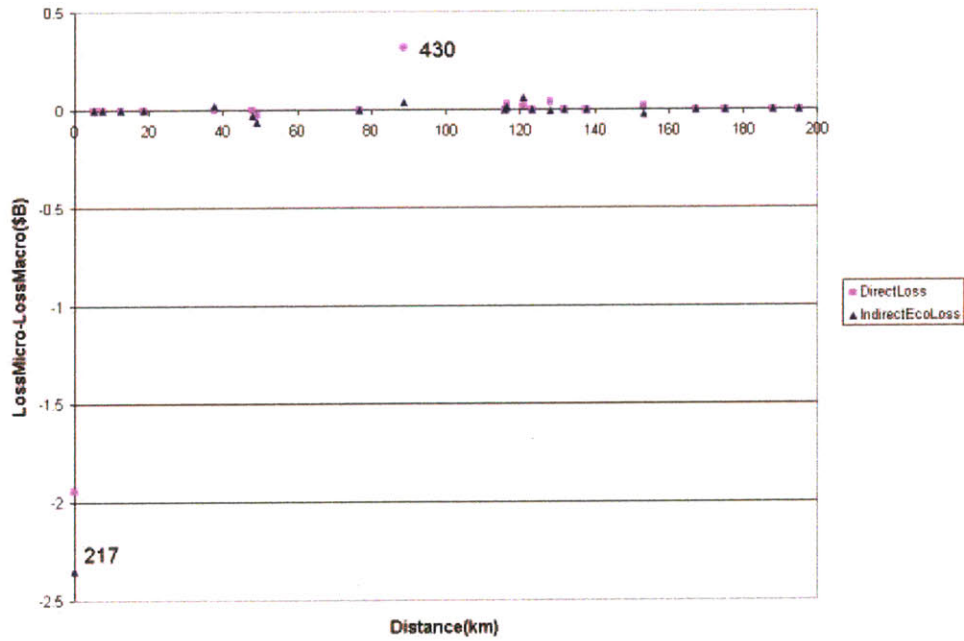


Figure 4-44: Change in losses from refining the analysis regions and network: macro-seismic approach, Scenario 1

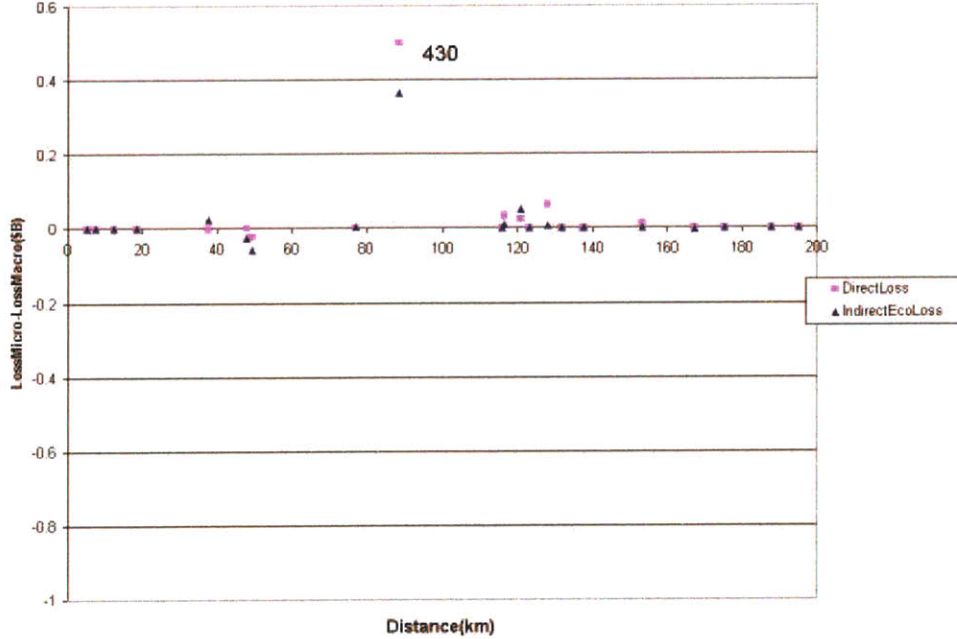


Figure 4-45: Change in losses from refining the analysis regions and network: engineering approach, Scenario 1

ference between the two scenarios, (Scenario 1 being the Shelby County earthquake), is in the spatial distribution of property around the epicenter. In Scenario 1, there is a large amount of property located near the epicenter but little property immediately outside the epicentral region, while the opposite is true for the second scenario. The difference in the spatial distribution of property in the two scenarios is illustrated in Figure 4-47. As was done for Scenario 1, sensitivity of the losses to the model resolution is evaluated using both the macroseismic and engineering approaches for Scenario 2 as well.

The losses from the low and high resolution models obtained using the macroseismic approach are given in Table 4.7. Table 4.8 gives the corresponding results obtained using the engineering approach. For scenario 2, there is less sensitivity of the losses to the resolution of the model. This is because the epicenter is located away from the region centroids and also because of the relatively low inventory levels near the epicenter, where damage changes rapidly with distance. As most of the property is located at distances where there is a slower rate of change of damage with distance,

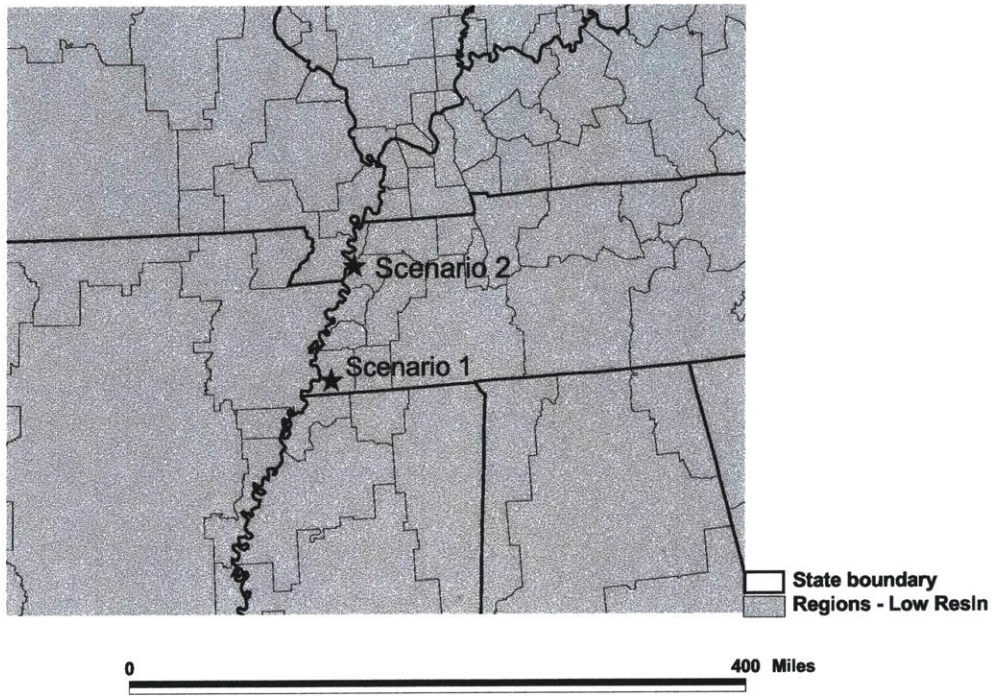


Figure 4-46: Scenario earthquakes

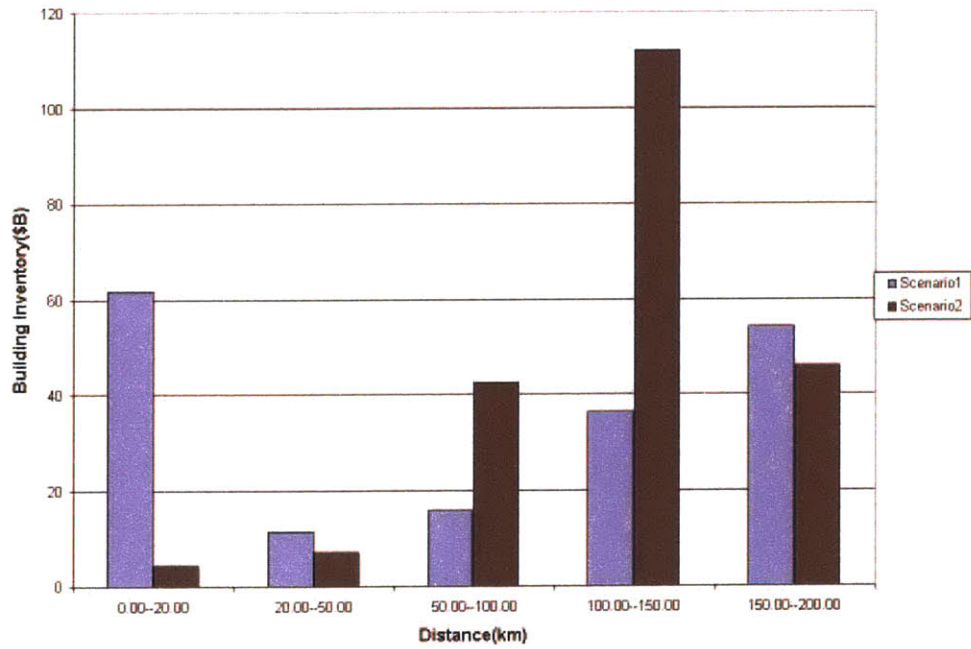


Figure 4-47: Spatial distribution of inventory in the two scenarios

Scenario 2 - Macroseismic	Low resolution network Low resolution regions	High resolution network High resolution regions
Building losses	105.8	106.0
Indirect economic losses	5.2	5.0
Indirect social losses	1.3	0.9

Table 4.7: Summary of losses: macroseismic approach, Scenario 2

Scenario 2 - Engg.	Low resolution network Low resolution regions	High resolution network High resolution regions
Building losses	8.2	8.1
Indirect economic losses	2.3	2.3
Indirect social losses	0.6	0.4

Table 4.8: Summary of losses: engineering approach, Scenario 2

the exact location of property is of lower importance since the damages at the refined regions and the original parent regions are approximately the same. Figures 4-48 and 4-49 show the change in the losses at the individual regions⁹ from increasing the model resolution, for the macroseismic and engineering approaches respectively. In the engineering approach, the direct losses from region 217 (Shelby County) decrease on refining it, while the indirect losses do not change (see Figure 4-49). The decrease in the direct losses is due to the aggregation of property in the low resolution model and its spatial disaggregation in the high resolution model. In the low resolution model, all properties are moved to the centroid, where there is some damage, while in the high resolution model, there are properties farther away from the epicenter than the centroid which suffer no damage at all. However, in both cases, the damages are below the minimum required to cause any drop in functionality and so there is no change in the indirect losses from increasing the model resolution.

For Scenario 2, while the losses are not very sensitive to the resolution of the model, they vary significantly depending on the modeling approach. Table 4.9 compares the high resolution model results for Scenario 2 produced by the macroseismic and engineering approaches. There is more than a ten-fold difference in the direct losses, while the indirect losses are in much better agreement. Also, if one compares the

⁹original, low resolution regions

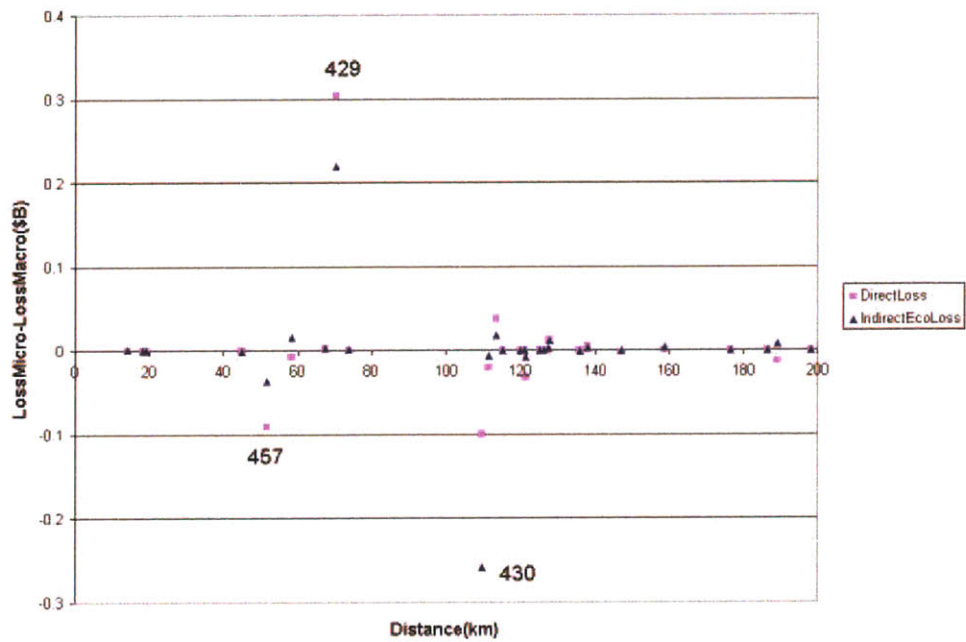


Figure 4-48: Change in losses from micro modeling the analysis regions and network, macroseismic approach, Scenario 2

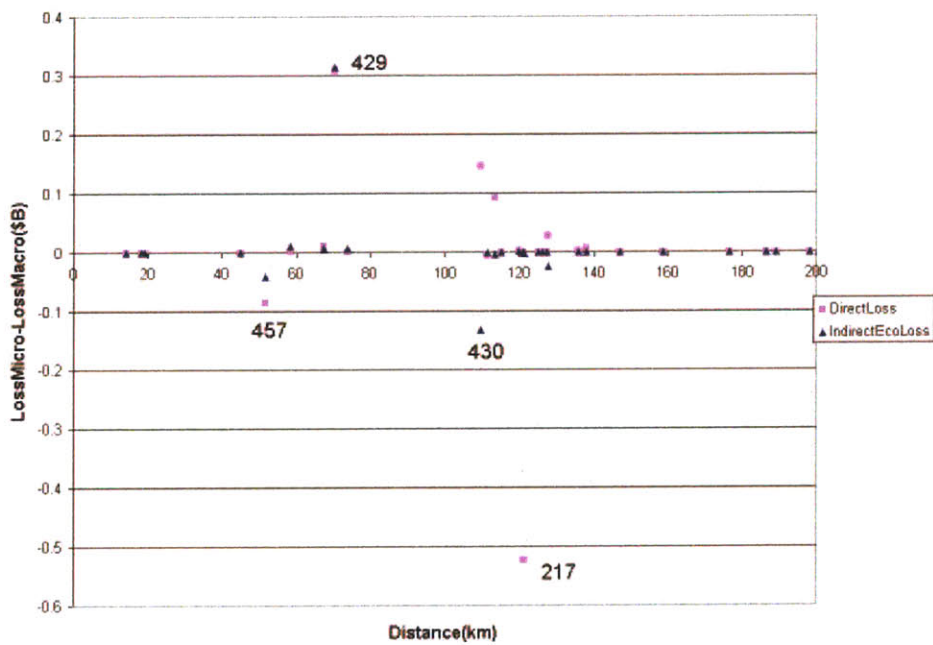


Figure 4-49: Change in losses from refining the analysis regions and network: engineering approach, Scenario 2

Scenario 2 - High resolution model	Macroseismic	Engineering
Building losses	106.0	8.1
Indirect economic losses	5.0	2.3
Indirect social losses	0.9	0.4

Table 4.9: Summary of losses: Macroseismic vs engineering, Scenario 2

macroseismic losses in the two scenarios (see Table 4.10), the direct losses do not change much, while the indirect losses decrease considerably from Scenario 1 to 2. Next, we give an explanation for these results.

- Comparison of the losses from the macroseismic and engineering approaches for Scenario 2

The reasons for the large difference in the direct losses without a corresponding change in the indirect losses are the same as in Scenario 1 - the slower attenuation of damage in the macroseismic approach and the non-linearity of functionality with damage. Figure 4-50 compares the distribution of the direct losses with distance from the epicenter in the two approaches and 4-51 shows the corresponding comparison of the indirect losses. Similar to Scenario 1, there is a large difference in the direct losses at distances beyond 200km - due to the slower attenuation of damage in macroseismic approach, while there is very little difference in the indirect losses at the same distances - due to the non-linear damage-functionality relation (note that the loss axis scale is different in Figures 4-50 and 4-51).

- Comparison of losses from the macroseismic approach in Scenarios 1 and 2

Figures 4-52 and 4-53 compare the distribution of the direct and indirect losses with distance in the two scenarios. The differences in the loss distributions reflect the differences in the spatial distribution of property and economic activity around the epicenters in the two scenarios (see Figure 4-47). The direct losses near the epicenter (within 20km) are lower in Scenario 2 compared to Scenario 1, while those from distances beyond 100km are higher. As the losses from beyond

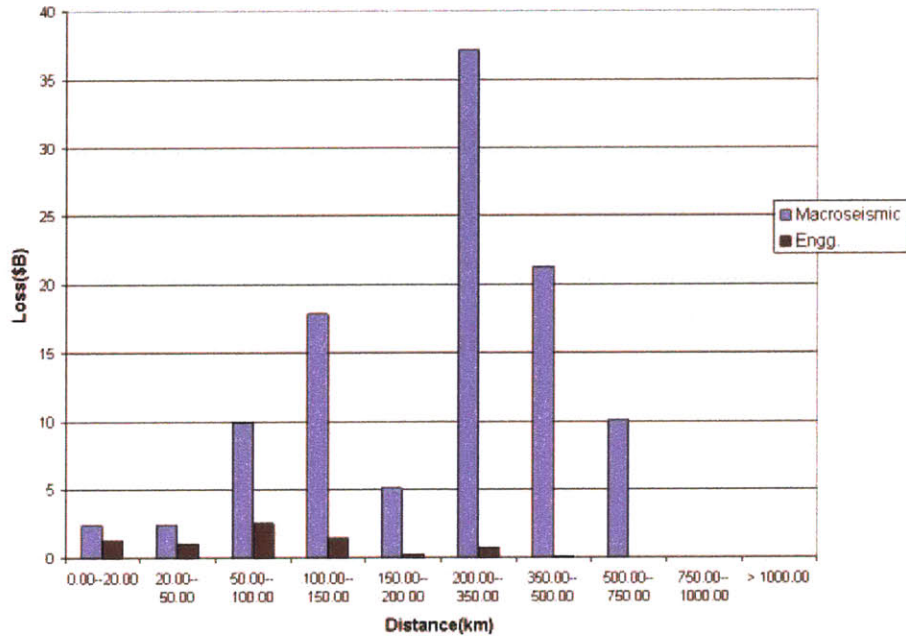


Figure 4-50: Comparison of distribution of direct losses with distance in Scenario 2: macroseismic vs engineering

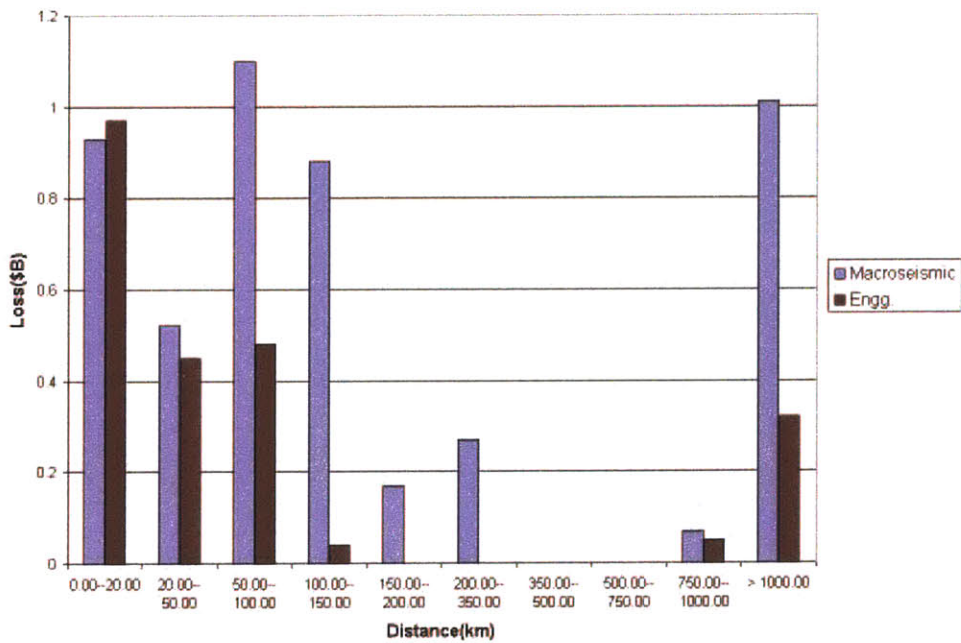


Figure 4-51: Comparison of distribution of indirect losses with distance in Scenario 2: macroseismic vs engineering

Macroseismic - High resolution model	Scenario 1	Scenario 2
Building losses	112.8	106.0
Indirect economic losses	22.1	5.0
Indirect social losses	1.6	0.9

Table 4.10: Summary of losses: macroseismic approach, Scenario 1 vs Scenario 2

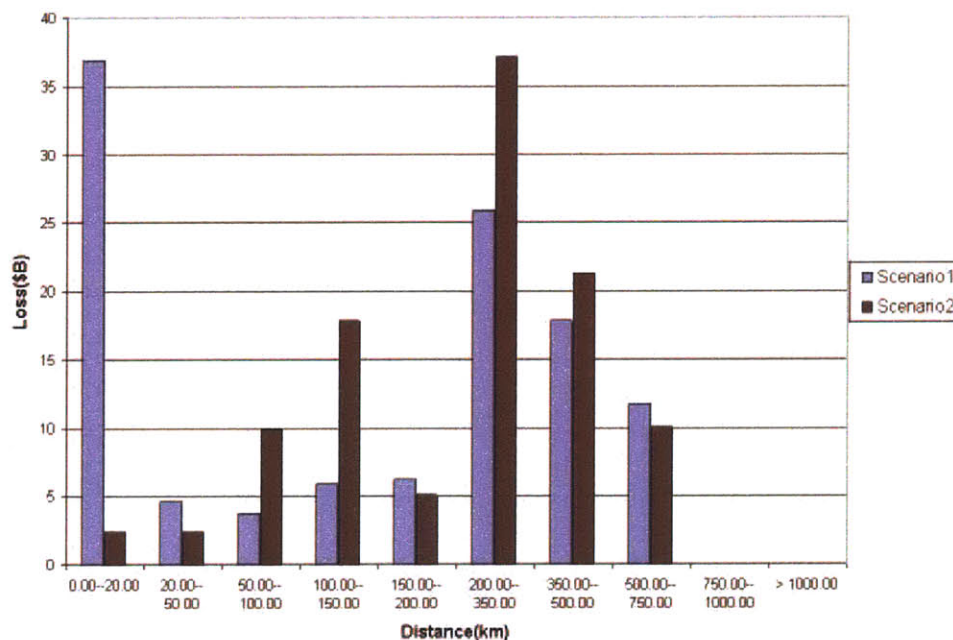


Figure 4-52: Comparison of distribution of direct losses with distance in the macroseismic approach: Scenario 1 vs Scenario 2

100km form a sizeable fraction of the total losses, the increase compensates for the decrease near the epicenter. In the case of the indirect losses, the losses near the epicenter are again much lower in Scenario 2 compared to Scenario 1. Although the losses from the farther regions do increase in Scenario 2, it does not compensate for the large decrease near the epicenter. This is because the losses from the farther regions represent only a small fraction of the total indirect losses.

The effects of increasing the resolution of the network and analysis regions on the losses have been analyzed for different earthquake locations and modeling approaches. The main results are summarized below and based on them some suggestions are given

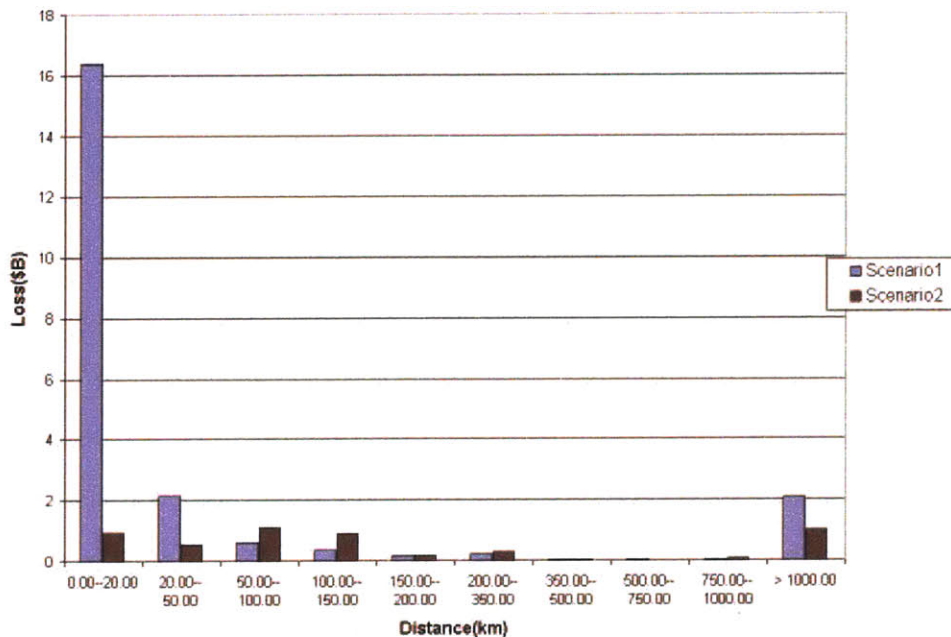


Figure 4-53: Comparison of distribution of indirect losses with distance in the macro-seismic approach: Scenario 1 vs Scenario 2

regarding the resolution needed in order to obtain accurate loss estimates.

Results:

- Increasing the resolution of the network affects different loss components and geographical locations than increasing the resolution of the analysis regions. Refining the network primarily affects the indirect social losses within and the indirect economic losses outside the regions where the network resolution is increased. In contrast, the effects of having a finer spatial discretization of the analysis regions are mainly restricted to the area of increased resolution.
- The effects of increasing the model resolution are greater at the local level than at the global level, i.e., the percentage change in the losses at individual regions is larger than the percentage change in the overall losses.
- The importance of having a refined model depends considerably on the earthquake location and modeling approach used. In some cases the losses are more and in other cases less sensitive to the resolution of the model.

- Going to a finer resolution adds to the computational complexity of the loss estimation methodology. Refining the analysis regions increases the memory requirements as there is more inventory and economic data to be stored. The running time also increases as there are more computations to be made. Refining the network increases the solution time of the network optimization algorithm considerably. Overall, the running time of the loss estimation procedure increases from about 30-45 minutes for the low resolution model of the regions and the network to about 2-2.5 hours for the high resolution model of the regions and the network. Running times are that on a standard current desktop (Pentium III, 700 Mhz, 256Mb).

Conclusions :

- Increasing the model resolution improves the accuracy of the loss estimates, especially at the local level. However, greater accuracy in the losses obtained from the increasing the model resolution is only meaningful in the context of a particular scenario and modeling approach. The large variation in the results when changing the scenario earthquake or modeling approach overshadows the effects of increasing the model resolution.
- The degree and the extent to which the model needs to be refined depends on the modeling approach used. For example, in the macroseismic approach, since damage remains constant within 10km of the epicenter, the model resolution within that distance range is of little importance. In contrast, in the engineering approach, as damage varies rapidly within the same distance range, it is very important have a high resolution of the model there. Also, regions beyond 100km need not be considered while refining the model in the engineering approach, as there is no damage beyond that. This is not the case in the macroseismic approach, where there is damage at those distances.
- The losses from the low and high resolution models agree reasonably well barring an extreme case. In the scenarios considered, the error in the losses from having

a coarser spatial discretization and network resolution is within $\pm\$0.2B$ ($\simeq \pm 30\text{-}40\%$) for most analysis regions. This suggests that the spatial discretization and network resolution of Gupta (2001) (low resolution model) is a reasonably robust one.

- The low resolution model results can be made more accurate with a small increase in computational cost. In order to do so, the model can be refined only inside regions 217 and 430, which have the greatest sensitivity to the model resolution. The network resolution within about 200km of the epicenter should be increased moderately to avoid errors from assigning regions to highway nodes far away from their centroids. The resulting model, with a resolution between the current low and high resolution models, would provide more accurate loss estimates than the low resolution one, while avoiding a significant increase in computational costs.
- This suggests the following spatial discretization strategy that may be used to obtain reasonably accurate loss estimates:

The procedure followed in Gupta (2001) (described in Chapter 3) can be used to obtain an initial model of the analysis regions and the transportation network. The analysis regions thus obtained are aggregations of counties. Analysis regions with the possibility of suffering earthquake damage and with a “large” amount of exposed property should be further discretized to the census tract level. In addition, the dimension of the regions in the radial direction from the earthquake epicenter should not be “too large”. Having analysis regions with a large dimension in the radial direction increases the error from calculating damage based on the centroid. Finally, the transportation network should be refined around the regions’ centroids to avoid associating the regions with far away highway nodes.

4.4 Sensitivity Results

Sensitivity analysis is carried out to assess the consequences of changing selected model parameters. Sensitivity of losses to the interaction coefficients (γ_{ji}, β_{ji}), the re-routing parameter (ρ) and alternative bridge classification systems and fragilities are assessed. In addition, the effects of ignoring the variability in building and bridge damage are illustrated. The sensitivity results are not comprehensive; rather their purpose is to illustrate the uncertainties in the loss estimates and motivate the need for quantifying them. The sensitivity runs are made using the high resolution model of the regions and the network for the 11.5MMI Shelby County scenario. The modeling approach used is the macroseismic approach.

- Sensitivity to the interaction coefficients: The interaction coefficients γ_{ji} and β_{ji} control the effect of the functionality of sector j on the functionality and recovery rate of sector i , respectively. As noted in Chapter 3, the interactions considered are effects of the lack of functionality of the residential sector and the transportation¹⁰ and utility lifelines on the functionality and recovery rates of the industrial and commercial sectors. The interaction coefficients have been judgmentally set to 1. Change in the losses by setting them to 0 (implying no interactions) are given in Tables 4.11 and 4.12 for γ_{ji} and β_{ji} respectively. The interaction effects of the transportation and utility lifelines is very small. This is because they recover rather quickly and are almost fully functional by the time the other sectors start recovering. The effects of the residential sector seems to be rather high, especially those of $\beta_{Res,j}$. A more realistic value of $\beta_{Res,j}$ may be 0.5 instead of 1.
- Sensitivity to the re-routing parameter: The re-routing parameter ρ is used to model the re-routing of traffic around damaged bridges. ρ has been judgmentally set to 0.25. The sensitivity of the losses as ρ varies from 0 (no re-routing around the damaged bridges) to 1 (complete traffic re-routing) is given in Table 4.13.

¹⁰The transportation system within an analysis region; not to be confused with the highways connecting the regions

	Indirect economic losses
Default values	22.1
$\gamma_{Res,i}=0 \forall i$	20.2
$\gamma_{Transp,i}=0 \forall i$	22.0
$\gamma_{Util,i}=0 \forall i$	22.0

Table 4.11: Sensitivity to γ_{ji}

	Indirect economic losses
Default values	22.1
$\beta_{Res,i}=0 \forall i$	18.7
$\beta_{Transp,i}=0 \forall i$	22.0
$\beta_{Util,i}=0 \forall i$	22.0

Table 4.12: Sensitivity to β_{ji}

The indirect losses are seen to be rather sensitive to the re-routing parameter. The losses vary in a non-linear manner as ρ changes from 0 to 1. There is greater sensitivity for low values of ρ , where the network is highly capacity constrained. There is little sensitivity for $\rho \geq 0.5$. This is because of the manner in which the pre-earthquake link capacities are set (refer Chapter 3). The pre-earthquake capacities are set so that there is an average link utilization of about 50%, which implies that there is sufficient capacity to transport the commodities for links operating at half their undamaged capacity. Therefore, at $\rho = 0.5$ there is sufficient network capacity and any additional capacity beyond that is of no use.

- Sensitivity to bridge classification system and fragilities: Sensitivity of losses to bridge classifications and fragilities alternative to those of HAZUS (2000) are assessed. The alternative classifications and fragilities considered are those

ρ	Indirect economic losses	Indirect social losses
0	26.0	3.9
0.15	23.3	2.3
0.25 (default)	22.1	1.6
0.5	20.3	1.4
1	20.2	1.3

Table 4.13: Sensitivity to re-routing parameter

Bridge classification	Indirect economic losses
HAZUS (2000)	22.1
Hwang et al. (1998)	22.3
DesRoches et al. (2002)	22.9

Table 4.14: Sensitivity to bridge classification system

	Indirect economic losses	Indirect social losses
Variability	22.1	1.6
No variability	36.2	2.8

Table 4.15: Sensitivity to variability in building damage

of Hwang et al. (1998) and DesRoches et al. (2002). Hwang et al. (1998) develop fragilities for 6 typical bridge types in the New Madrid region. Bridges are classified primarily based on the pier and bent type. Two damage states are considered : repairable and significant damage. For each bridge, fragility curves give the probability of exceeding these damage states. DesRoches et al. (2002) develops fragilities for 6 typical Mid-America bridges. The bridge classification is based on the construction material and number of spans. Four damage states are considered, namely slight, moderate, extensive and complete. Table 4.14 gives the sensitivity results to the alternate classifications and fragilities. The indirect losses do not vary much, which indicates similar levels of network disruption in all cases and suggests that the different classifications are consistent.

- Sensitivity to variability in damage: There is variability in damage within infrastructure elements of the same type due to differences in structural design, construction, age of the structure etc. Accounting for the variability in damage affects the indirect economic losses because of the non-linear damage-functionality relation. The indirect losses with and without variability in damage are compared, for both buildings and bridges. Table 4.15 gives the results for buildings and Table 4.16 for the bridges. As noted in Chapter 3, the indirect losses increase on ignoring the variability in building damage, while the opposite is true in case of bridges.

	Indirect economic losses	Indirect social losses
Variability	22.1	1.6
No variability	21.8	1.4

Table 4.16: Sensitivity to variability in bridge damage

4.5 Retrofit Measures

The possible remedial measures considered are the retrofitting of unreinforced masonry buildings by changing their fragility to that of reinforced masonry, “hardening” the transportation network so that there is no pavement or bridge damage, speeding up recovery of the transportation network (doubling the recovery rate of pavements and bridges) and a similar speeding up of recovery of the economic sectors. In addition, the effect of slower recovery (twice the normal recovery time) of the transportation network is considered - which is more of a sensitivity analysis. The results are obtained using the high resolution model for the Shelby County scenario with the macroseismic approach.

Table 4.17 summarizes the results. Retrofitting of the unreinforced masonry buildings brings about large reductions in the direct and indirect economic losses. Doubling the recovery rate of the economic sectors brings about the greatest decrease in the indirect economic losses, roughly reducing them by half. In contrast, completely retrofitting the transportation network or speeding up its recovery, does not affect the indirect economic losses very much. This suggests that most of the indirect losses are due to damage and losses due to commodity flow disruption are only secondary. The indirect social losses are more sensitive to the retrofitting and faster recovery of the transportation network, as the additional commodity flows are used to satisfy the domestic consumptions. Finally, there is greater effect when the network recovery is slowed down than when it is speeded up. This has to do with the relatively fast recovery of the network compared to that of the economic sectors. Therefore, further speeding up of the network recovery has little effect. However, slowing down the network recovery affects the industries, which are functional by then, as they have to reduce their productions, since their net exports and imports are not satisfied. Notice

Strategy/change	Direct building losses	Indirect economic losses	Indirect social losses
Base case	112.8	22.1	1.6
Retrofit of UM buildings	79.6	18.8	1.5
Faster recovery of economic sectors	112.8	12.8	1.5
Hardening the network	112.8	19.9	0.3
Faster network recovery	112.8	21.7	1.5
Slower network recovery	112.8	23.1	2.2

Table 4.17: Effect of mitigation measures

that this analysis is not sufficient to rank the different remedial measures, since the costs associated with them are vastly different and the individuals or organizations that would have to bear such costs are not the same.

To summarize, sensitivity of the losses to the model resolution, the modeling approach and selected model parameters have been examined. In addition, the loss reductions from certain mitigation strategies have been evaluated. While the increasing the model resolution does influence the losses, the effects are secondary compared to the sensitivity to the modeling approach and model parameters. This motivates the need to comprehensively quantify these uncertainties. The concluding chapter discusses such issues and the scope for further work to improve the loss estimation methodology.

Chapter 5

Conclusions

This thesis advances the loss estimation of Gupta (2001) to estimate the earthquake losses at the local, regional and national levels in an integrated, comprehensive manner. The main issues addressed are the sensitivity of the losses to the resolution of the model and to alternative formulations of ground motion and damage. First, the main results of this thesis are summarized. Then, scope for further research is pointed out.

5.1 Main Results

The main accomplishments of this research are:

- Comprehensive estimation of earthquake losses at local, regional and national scales. Numerical results are presented for scenario New Madrid earthquakes
- Understanding how losses change with the spatial resolution at which they are estimated
- Evaluating losses using alternative modeling approaches to characterize ground motion and damage, namely the “macroseismic” and “engineering” approaches.

Previous efforts (Cho et al. (2000), Werner et al. (2000), Sohn et al. (2001a,b), HAZUS (2000), Gupta (2001)) have not explicitly considered the how the loss estimates vary with the resolution at which the methodology operates. The spatial resolution is an important issue, as it determines the accuracy of the loss estimates and

also the numerical feasibility and computational complexity of the methodology. Previous efforts have also followed either the “macroseismic” or “engineering” approaches to estimate the losses. The “macroseismic” approach refers to the more qualitative, judgmental approach to earthquake loss estimation, with parameters based on observations of earthquake damage, historical records and expert opinion. Earthquake losses have been traditionally estimated in this manner. The “engineering” approach refers to the more recent, quantitative method, with parameters based on instrumental recordings and engineering analysis. It is useful to evaluate losses using both approaches and compare them, since the two approaches have different underlying assumptions, which may not be mutually consistent. This comparison also provides a sense of the uncertainty in the loss estimates.

The review of literature indicates that while there are many advanced earthquake loss estimation methodologies addressing highly complex issues, most are limited in terms of geographical scale (restricted to local or regional level) or scope (only certain loss components considered). The methodology of Gupta (2001) is the only one that evaluates losses comprehensively at the national level. Gupta (2001) evaluates the direct and indirect economic losses due to earthquakes at the national level, specially accounting for the effects of transportation network damage. This thesis uses the methodology of Gupta (2001) as a base and improves on it.

Gupta (2001) divides the conterminous U.S. into a number of “analysis” regions around the nodes (highway intersections) of the road transportation network. The analysis regions are aggregations of counties. The population, building inventory and economic activity of the associated counties are treated as being concentrated at the region’s population centroid. The population centroid of a region is the weighted average of the geometric centroids of the counties comprising that region, using weights proportional to population. Each analysis region is associated with the highway node closest to its centroid. The road transportation network consists of all the interstate highways augmented by some state highways, but only near the epicenter. In the scenario considered, the epicenter is located in the New Madrid region. The nodes of the network are the highway intersections, while the links are the highway seg-

ments connecting them. Bridges are modeled only in the New Madrid region and are associated with the closest highway segment.

The methodology considers damage to the infrastructure elements, their loss-of-functionality and recovery over time. The effects of disruption to the transportation and utility lifelines and unavailability of labor on the functionality and recovery rates of the industrial and commercial sectors are modeled, although in a coarse manner. This is done by specifying interaction coefficients, which control the effects of the functionality of the lifelines and the residential sector on the functionality and recovery rates of the industrial and commercial sectors. Inter-industry interactions are quantified using an economic input-output model. Inter-regional interactions are captured through a network analysis model.

The improvements made in the methodology of Gupta (2001) include:

- **Incorporation of the engineering approach:** Gupta (2001) uses the macroseismic approach to evaluate earthquake losses. The intensity unit used is the Modified Mercalli Intensity (MMI), the Bollinger (1977) attenuation relation is used and fragility curves are based on ATC-13 (1985). More recent advances in the earthquake engineering field are incorporated into the methodology. This is the engineering approach, which uses the attenuation relation and soil map of Toro and Silva (2001), soil amplification factors of Dobry et al. (2000) and fragility curves from HAZUS (2000).

Losses are evaluated using both approaches for scenario New Madrid earthquakes. The direct economic losses obtained using the macroseismic are much higher (3-10 times as much) than those from the engineering approach, while the indirect losses are comparable. The difference in the direct losses comes from mainly from regions further away from the epicenter ($\geq 200\text{km}$), where the damage attenuates more slowly with distance in the macroseismic approach compared to the engineering one. However, the indirect losses from the same distances ($\geq 200\text{km}$) are almost zero in both approaches. This results from the non-linearity of functionality with damage. There is a minimum level of dam-

age needed to cause any loss-of-functionality and in both cases the damages are below this threshold value.

- Consideration of variability in damage: The methodology of Gupta (2001) is completely deterministic. Uncertainty is considered, although in a very incomplete manner. The effect of variability in damage on the expected losses is considered. There is variability in damage to infrastructure elements of the same class (say, unreinforced masonry buildings) because of differences in structural design, construction, age etc. Considering this variability affects the initial average functionality and therefore the indirect economic losses. In the case of buildings, considering the variability in damage results in decreased indirect economic losses, while the opposite is true in the case of bridges.

Sensitivity of the losses to the consideration of variability in damage is rather large for buildings (-40%). The sensitivity is much less in the case of bridges (+1%).

- Calibration of pre-earthquake link capacities: As Gupta (2001) does not model passenger flows and cross-hauling of commodities, links have low pre-earthquake utilizations (flow/capacity). This underestimates the importance of the transportation network in the post-earthquake scenario, since even at reduced capacities, most links would be able to carry all the flows. In order to better model the effects of network disruption, link capacities in the New Madrid regions are set based on the average daily traffic (ADT) data (available from the NBI (Federal Highway Administration (FHWA) (1995)) on its bridges, while link capacities outside are set based on their pre-earthquake flows. Setting the capacities in this manner results in an average link utilization of about 50%, which is considered to be reasonable.
- Modeling the effects of secondary roads: The transportation network does not include most of the secondary roads (U.S. highways and county roads), which could be critical in the post-earthquake scenario for re-routing of traffic around damaged bridges on the interstate highways. This is modeled in a coarse manner

through the “re-routing” parameter ρ , which controls the effect of the bridges in determining the overall link capacity. $\rho = 0$ implies that no re-routing around damaged bridges, while $\rho = 1$ implies complete re-routing. ρ is judgmentally set as 0.25. Losses are rather sensitive to the re-routing parameter especially for ρ between 0 and 0.5.

- Improved loss measures: Gupta (2001) evaluates the direct and indirect losses at the national level. These are disaggregated in space and time and by economic sector. The residential sector contributes the most to the direct economic losses, as dwellings make up a large fraction of the infrastructure value. For a similar reason, the commercial/services sector contributes the most to the indirect economic losses.

Additional losses are quantified, such as those due to increased transportation costs (taken to be the ratio of the cost of routing commodities on a damaged network to that of routing them on an undamaged network), indirect social losses (due to unmet domestic demand) and social losses due to casualties. Losses due to increased transportation costs change over time due to the differential recovery of the industries and the transportation network. For example, if the industries recover faster relative to the network, then the commodity flow on the network increases while the capacity remains the same. Therefore, commodities have to be routed along longer paths, increasing the transportation costs. The opposite is true if the industries recover slower relative to the network. The transportation losses are comparable with that predicted by Sohn et al. (2001a). However, as Sohn et al. (2001a) do not model the recovery process, they predict constant losses over a period of 1 year.

- Increasing the model resolution: A major focus of this thesis has been in understanding how the loss estimates vary with the resolution of the model. The analysis regions and the network are refined within a radius of roughly 100km from the epicenter. The resolution of the analysis regions is increased to the census tract level from the county level. County roads and U.S highways are

also modeled in addition to the state and interstate highways in the region of increased resolution.

Comparison of losses with the “low” resolution model reveal errors from having a coarse resolution, which for most analysis regions is within $\pm 30\text{-}40\%$. The errors are due to:

- Non-linearity in the damage-distance relation and the aggregation of property at the centroids.
- Incorrect assignment of regions to highway nodes in a sparse network
- Underestimating the network redundancy

The effects of non-linearity in the damage-distance relation and the incorrect assignment of regions to highway nodes result in increased losses in some regions and decreased losses in others, depending on the spatial distribution of property in the region and the highway node with which it is associated in the low resolution model. Increasing the redundancy of the network results in decreased losses due to lesser commodity flow disruption. On the whole, the effects compensate for each other at some regions, while the errors are amplified at others.

On the basis of the comparisons between the “low” and “high” resolution models, certain suggestions are made that may be used to obtain reasonably accurate loss estimates. Within the earthquake affected region, resolution at the county level is sufficient for most analysis regions. For regions with a “large” amount of exposed property, further discretization to the census tract level is required. To give an example, in the New Madrid scenarios, Shelby County which accounts for nearly 50% of the property within a radius of 200km of the epicenter, is further refined to the census tract level. The transportation network should also be refined around the regions’ centroids to avoid errors from associating regions with far away highway nodes.

- Improved bridge classification system: The rather coarse ATC-13 (1985) bridge classification (3 types) is replaced by the more sophisticated National Institute of Building Sciences (2000) classification (28 types), which classifies bridges based on year built, number of spans, span length and construction material. Sensitivity of losses is evaluated to alternative bridge classification systems and fragilities (Hwang et al. (1998), DesRoches et al. (2002)). There is low sensitivity indicating that the different classifications are consistent.

Other result obtained include :

- Sensitivity to interaction effects of the lifelines and the residential sector: The effects of disruption to the transportation and utility lifelines on the functionality and recovery rates of the industrial and commercial sectors are small (1% increase relative to when there are no interactions), since the lifelines recover rather quickly relative to these sectors and are almost fully functional by the time they start recovering. The interaction effects of the residential are larger - 10% and 20% increase in the indirect losses on including interaction effects of the residential sector on the functionality and recovery rate, respectively. This is because it recovers at a comparable rate to the industrial and commercial sectors. Therefore, they are affected by the reduced functionality of the residential sector.
- Sensitivity to earthquake location: Losses are sensitive to the location of the epicenter due to the non-uniform distribution of property in the New Madrid region. There is a large amount of property in Shelby County, TN but little property immediately outside it. Therefore, locating the earthquake epicenter within Shelby County produces higher losses than when the epicenter is located away from it.
- Remedial measures: Remedial measures considered include retrofitting of unreinforced masonry buildings, hardening the transportation network and speeding up the recovery of the economic sectors and the network beyond the “normal”

non-emergency rates. Retrofitting of the unreinforced masonry buildings and speeding up the recovery of the economic sectors bring about the greatest reductions in the direct and indirect economic losses, respectively. The social losses are more sensitive than the economic losses to hardening the transportation network or speeding up its recovery. This is because the additional commodity flows are used to satisfy the domestic consumptions. The industries being non-operational (due to damage) do not have major demands and so are not significantly affected by the additional flows.

5.2 Future Research Directions

In view of the large variation in the loss estimates, there is a very urgent need to quantify the uncertainties in all component model parameters and incorporate them into the loss estimates. Another area that needs to be looked into is the validation of the results of the methodology. Due to lack of historical data on earthquake losses in the New Madrid region and the absence of comparable studies, it is difficult to assess the realism of the results. In order to validate them, the methodology has to be applied to regions with past records of earthquake losses. However, this would involve a significant amount of work, since the model data and parameters have to be calibrated to the particular region of application.

More specific issues that need to be addressed include:

- Optimal spatial discretization of the analysis regions and resolution of the network.
- Alternative allocations of the regions' net exports to the transportation network. For example, instead of associating the region with a single highway node, one may assign portions of it to multiple nodes. This would possibly make the loss estimates less sensitive to the resolution of the model, since the assignment of regions to nodes would not change drastically on refining them.
- Obtaining reliable building inventory and economic data at a disaggregate level.

This would improve the accuracy of the loss estimates by better representing the actual spatial distribution of property and economic activity and by eliminating errors resulting from disaggregating data.

- Understanding and resolving the differences in the attenuation and fragility relations in the engineering and macroseismic approaches. Resolving the differences would reduce uncertainty in the loss estimates. However, understanding and resolving the differences in the two approaches is not trivial as they have different underlying assumptions, with very little common ground for making comparisons.
- Modeling the inventory of the economic sectors. The methodology does not model the buffering effects of inventory which could absorb some of the supply shock from the earthquake affected regions. Also, the methodology assumes that all commodities not transported within a certain time window (discrete time step) are lost to the system. Modeling inventory accounts for the fact that the flow of commodities may be staggered over time, i.e, goods may be stored at the current time step and sent later. The main issue in modeling inventory is in obtaining accurate estimates of the inventory levels of the economic sectors at the regions. In addition, the complexity of the problem increases since decisions have to be made whether to store commodities at the current time step or to transport them in spite of the high cost.
- Improving the transportation models to include network congestion, cross hauling of commodities, passenger flows and multi-modal flows. Congestion can be modeled by having a non-linear link cost function. However, this increases the complexity of the problem as non-linear problems are in general much harder to solve than linear ones. Modeling of cross-hauling and passenger flows require considering OD flows or a path based formulation, which is typically harder to solve than link based one. Multi-modal flows such as modeling freight flows on the road and rail networks adds to the complexity as multiple networks and interactions among them have to be considered.

- Assigning of flows in the network and calculating the industrial productions and domestic consumptions simultaneously instead of using an iterative approach. The entire problem can be solved as a large linear program. While this would give a provably optimal solution, the computational complexity increases as there are many more variables and constraints (network flow constraints and the input-output constraints at *all* the analysis regions).
- The methodology can be extended to other disasters. For example, there is interest in this modeling approach to assess anti-terrorism strategies.
- Using the methodology to assess the effectiveness of alternative loss mitigation strategies.

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