Executive Summary

1. Introduction

Lifeline is an earthquake engineering term denoting those systems necessary for human life and urban function, without which large urban regions cannot exist. Lifelines basically convey food, water, fuel, energy, information, and other materials necessary for human existence from the production areas to the consuming urban areas. Prolonged disruption of lifelines such as the water supply or electric power for a city or urbanized region would inevitably lead to major economic losses, deteriorated public health, and eventually population migration. Earthquakes are probably the most likely natural disaster that would lead to major lifeline disruption. With the advent of more and more advanced technology, the United States has increasingly become dependent on the reliable provision of lifeline-related commodities, such as electric power, fuel, and water. A natural question is: What is the potential for major disruption to these lifelines, especially at the regional level?

The initiation of this study by the Federal Emergency Management Agency (FEMA) is based in part on a need to better understand the impact of disruption of lifelines from earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies. In addition, the report is intended to improve national awareness of the importance of protecting lifeline systems from earthquakes, and of assuring lifeline reliability and continued serviceability.

The specific contractual requirements of this project and report are:

- To assess the extent and distribution of existing U.S. lifelines, and their associated seismic risk; and
- To identify the most critical lifelines, and develop a prioritized series of steps for reduction of lifeline seismic vulnerability, based on overall benefit.

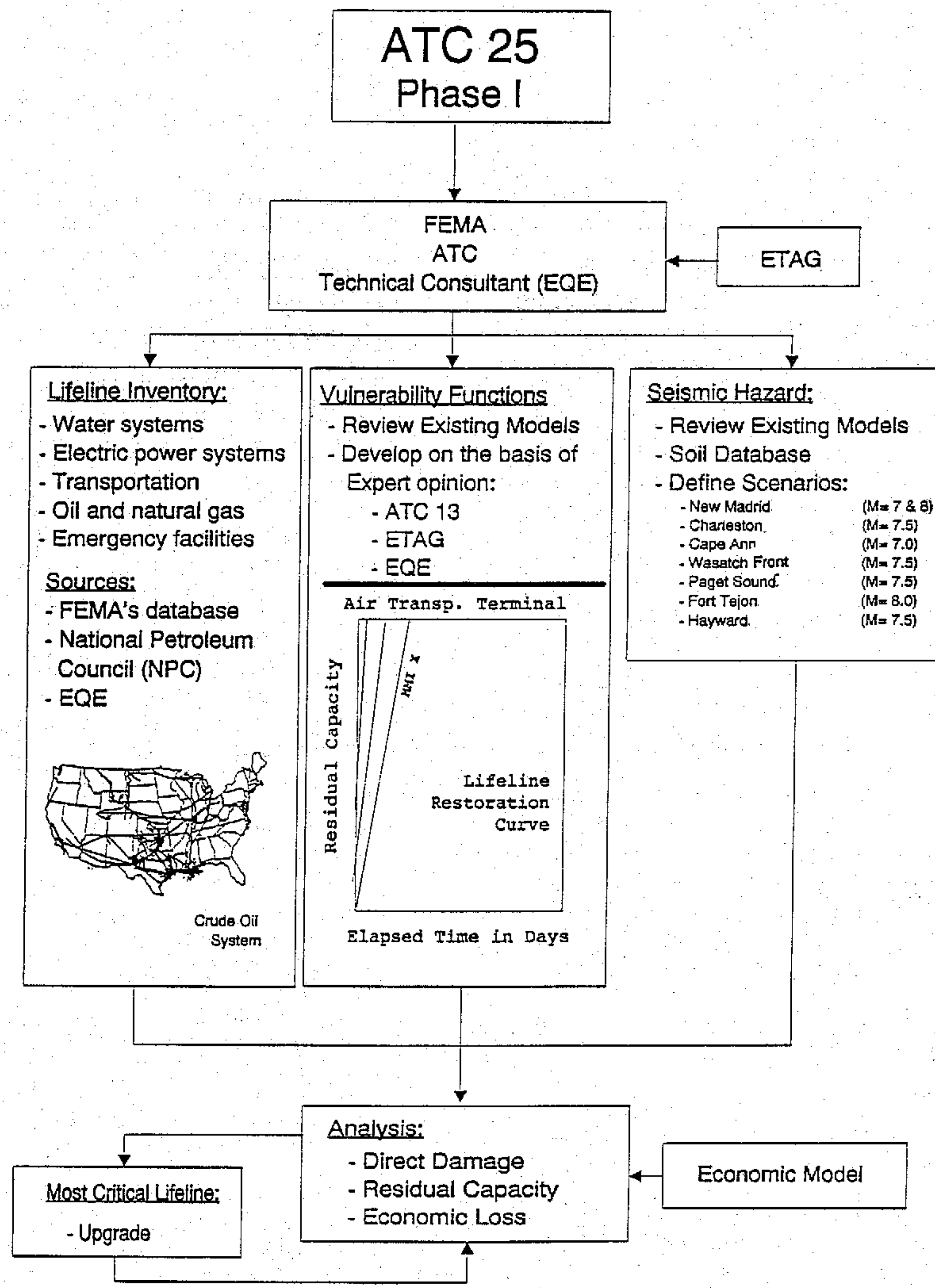
FEMA is also sponsoring a companion study to develop and demonstrate a model methodology for assessing the seismic vulnerability and impact of disruption of water transmission and distribution systems (ATC, in preparation).

In this initial study, lifelines of critical importance at the U.S. national level have been analyzed to estimate overall seismic vulnerability and to identify those lifelines having the greatest economic impact, given large, credible U. S. earthquakes. The lifelines examined include electric systems; water, gas, and oil pipelines; highways and bridges; airports; railroads; ports; and emergency service facilities. The vulnerability estimates and impacts developed are presented in terms of estimated direct damage losses and indirect economic losses. These losses are considered to *represent a first approximation* because of the assumptions and methodology utilized, because several lifelines are not included, and because, in some cases, the available lifeline inventory data lack critical capacity information.

Project Approach. As summarized in the project technical-approach flow chart (Figure 1), four basic steps were followed to estimate lifeline damage and subsequent economic disruption for given earthquake scenarios.

1. Development of a national lifeline inventory database.
2. Development of seismic vulnerability functions for each lifeline component/system,
3. Characterization and quantification of the seismic hazard nationwide, and
4. Development of direct damage estimates and indirect economic loss estimates for each scenario earthquake.

Limitations and Constraints. During development of this report and its supporting data, several problems were encountered that could not be resolved because of technical difficulties and lack of available data. For example, telecommunication systems, nuclear and fossil-fuel power plants, dams, and certain water, electric, and transportation facility types at the regional transmission level were excluded from consideration in this project because of the



Notation: ATC-13: ATC-13 Report, *Earthquake Damage Evaluation Data for California* (ATC, 1985)
ETAG: Expert Technical Advisory Group (project advisory panel)
EQE: EQE Engineering (project subcontractor)

Figure 1 Flow chart showing main steps in project approach.

unavailability of inventory data or the need for more in-depth studies.

Interaction effects between lifelines, secondary economic effects (the impact of a reduced capacity of one economic sector on a dependent sector), and damage resulting from landslide (due to lack of inventory data nationwide) were also not considered in developing this report. These limitations and others described in Chapters 2, 4, and 5 tend to underestimate the losses presented herein; and other factors, as described elsewhere in this report, tend to overestimate the losses. Lack of capacity information for most lifelines was also a definite limitation. In the aggregate, due primarily to the exclusion of certain systems (e.g., dams and telecommunication systems), we believe the estimates of losses presented in this report are, in fact, quite conservative.

We also emphasize that this report is a macroscopic investigation at the national level and the results should not be used for microscopic interpretations. The results, for example, are not intended to be used to evaluate any particular regional utility or lifeline, and no specific information on such specific facilities has been included.

2. National Lifeline Inventory

Development of the ATC-25 inventory, for all major lifelines in the United States, was a major task. The project scope required that lifelines be inventoried in sufficient detail for conducting lifeline seismic vulnerability assessments and impact of disruption at the national level. This in turn required that the inventory be compiled electronically in digital form and dictated that inclusion of lifelines at the transmission level, as defined below, was of primary importance.

Initially, a number of government, utility, trade and professional organizations, and individuals were contacted in an effort to identify nationwide databases, especially electronic databases. In most cases, these organizations or individuals referred the project back to FEMA, since they had either previously furnished the information to FEMA, or knew that the data had been furnished to FEMA by others. As a result, FEMA's database (FEMA, 1987) became a major source of data for several of the lifelines. A significant portion of these data consist of digitized U.S. Geological Survey (USGS) topographical maps and/or the National Atlas (Gerlach, no date), performed by the U.S. Geological Survey in support of national census requirements. With the exception of oil and gas pipeline data provided by the National Petroleum Council, the inventory data generally date from about 1966, unless later updated by FEMA. A number of other sources were employed in various ways, which are further discussed below.

The network inventory contained in the database is generally at the higher transmission levels, as opposed to lower distribution levels. That is, inventories were generally only compiled for networks at the bulk and/or regional level, as opposed to lifelines at the user-level (i.e., distribution level) *within* an area. To use an analogy, the inventory contains only the national *arterial* level, and neglects the distribution or *capillary* system. For example, all federal and state highways are inventoried (Figure 2), but county and local roads are not. The major reason for focusing on the transmission level is that at lower levels the systems only support local facilities. Thus, a disruption of a local activity could not be used to identify the overall regional importance of the lifeline. However, disruptions at the transmission level impact large regions and are therefore important for understanding the seismic vulnerability and importance of lifelines to the United States.

Inventory Overview. The inventory data (Chapter 2) have been compiled into an electronic database, which generally consists of (i) digitized location and type of facility for single-site lifeline facilities, and (ii) digitized right-of-way, and very limited information on facility attributes for network lifelines. The inventory is only a partial inventory, in that important information on a number of facility attributes (e.g., number or length of spans for highway bridges) was unavailable from FEMA.

The inventory data include information for the conterminous United States only. Lifeline data for Alaska, Hawaii, and U. S. territories, such as Puerto Rico, have been excluded because lifelines in these regions would not be affected by the scenario earthquakes (see Chapter 4) considered in this study.

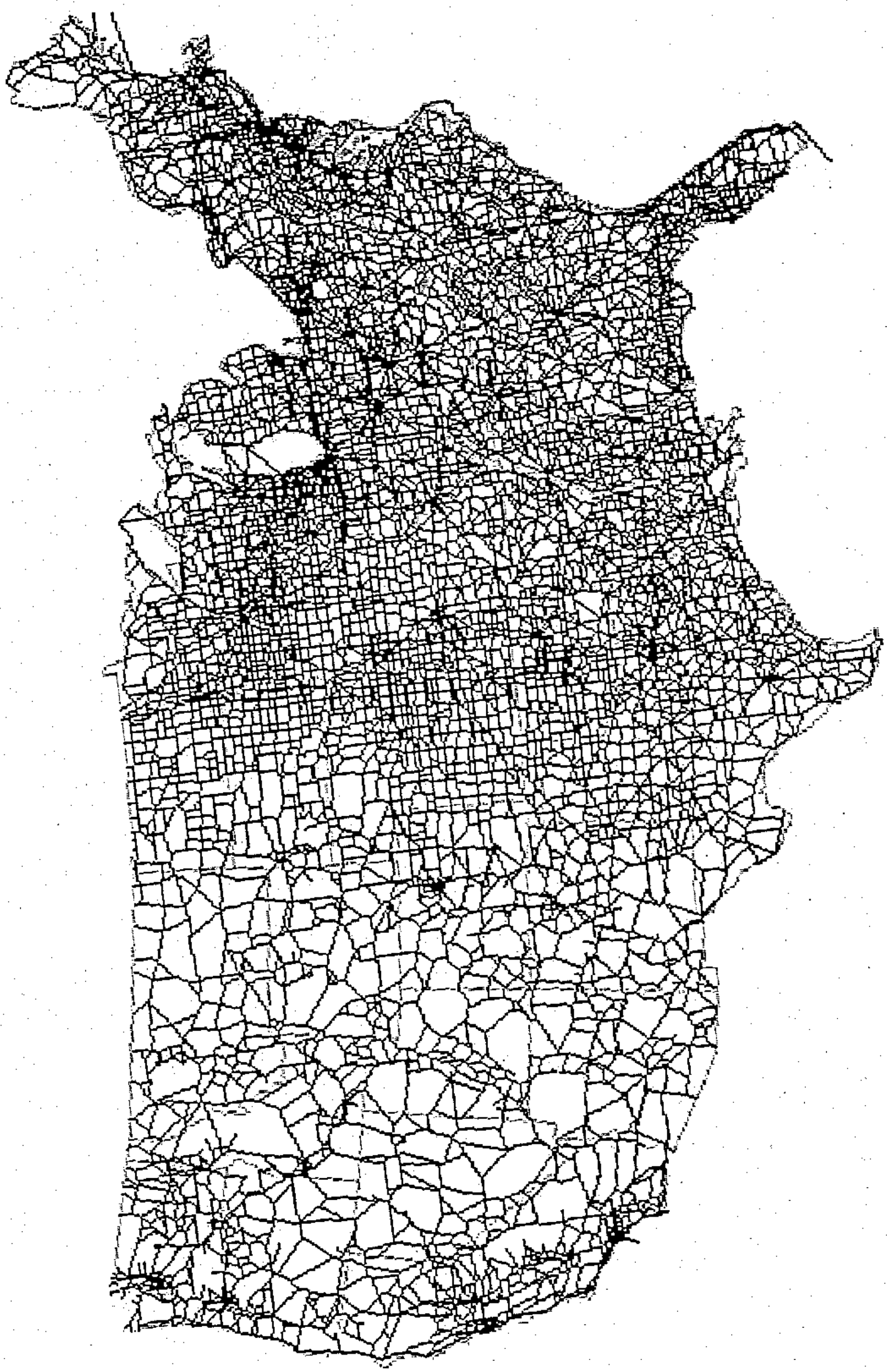


Figure 2 *State and federal highways.*

The specific lifelines that have been inventoried for the conterminous United States are:

Transportation

- Highways (489,892 km of highway (Figure 2); 144,785 bridges)
- Railroads (270,611 km of right-of-way)
- Airports (17,161 civil and general aviation airports)
- Ports (2,177 ports)

Energy

- Electric Power Transmission (4,551 substations; 441,981 km of transmission lines)
- Gas and Liquid Fuel Transmission (77,109 km of crude oil pipelines; 85,461 km of refined oil pipelines; 67,898 km of natural gas pipelines.)

Emergency Service Facilities

- Emergency Broadcast Facilities (29,586 stations)
- Hospitals (6,973 medical care centers)

Water Aqueducts and Supply (3,575 km of aqueduct; excludes aqueducts in Utah, which were unavailable)

An important lifeline, telecommunication systems, which would be severely impact by earthquake-induced ground shaking, was excluded because of the unavailability of data, as are certain regional transmission network facility types (e.g., railway terminals, bridges, and tunnels; certain aqueducts; major freeway/highway bridges; fossil-fuel power plants; and aqueduct pumping stations). In addition, data on nuclear reactors and dams are excluded because it was believed that such facilities should be the subject of special studies, particularly because of the existing regulations relating to seismic safety in many regions and the expected complexity of the performance and impact of these facility types. As a result, the losses provided by this study will be underestimated to the extent that these facility types are not included.

Also excluded from the inventory, but included in the analysis, are distribution systems at the local level (water, highway, and electrical systems) and police and fire stations. For these facility types, the number of facilities in each 25-km by 25-km grid cell, which is the grid size for the seismic hazard analysis, is estimated on the basis of proxy by population (see Chapter 2).

PC-Compatible Electronic Database. Because the data could also serve as a valuable framework (or starting point) for researchers who wish to investigate lifelines at the regional or local level, including applications unrelated to seismic risk, the data have been formatted for use on IBM-PC compatible microcomputers. The data are unrestricted and will be made available by ATC on 18, 1.2-megabyte, floppy diskettes, together with a simple executable computer program for reading and displaying the maps on a computer screen.

3. Lifeline Vulnerability Functions

The second step in the project was the development of lifeline vulnerability functions, which describe the expected or assumed earthquake performance characteristics of each lifeline as well as the time required to restore damaged facilities to their pre-earthquake capacity, or usability. Vulnerability functions were developed for each lifeline inventoried, for lifelines estimated by proxy, and for other important lifelines not available for inclusion in the inventory. The components of each vulnerability function and how they were developed are described in Chapter 3; the functions themselves, too lengthy to include in the main body of the report text, are provided in Appendix B.

The vulnerability functions developed for each lifeline consist of the following components:

- *General* information, which consists of (1) a *description* of the structure and its main components, (2) *typical seismic damage* in qualitative terms, and (3) *seismically resistant design* characteristics for the facility and its components in particular. This information has been included to define the assumed characteristics and expected performance of each facility and to make the functions more widely applicable (i.e., applicable for other investigations by other researchers).

- Direct damage information, which consists of (1) a description of its basis in terms of structure type and quality of construction (degree of seismic resistance), (2) default estimates of the quality of construction for present conditions and corresponding *motion-damage curves*, (3) default estimates of the quality of construction for upgraded conditions, and (4) *restoration curves*.

These functions reflect the general consensus among practicing structural engineers that, with few exceptions, only California and portions of Alaska and the Puget Sound region have had seismic requirements incorporated into the design of local facilities for any significant period of time. For all other areas of the United States, present facilities are assumed to have seismic resistance less than or equal to (depending on the specific facility) that of equivalent facilities in California NEHRP Map Area 7 (Figure 3). Three regions, representing these differences in seismic design practices, are defined for the United States:

a. California NEHRP Map Area 7, which we take to be the only region of the United States with a significant history of lifeline seismic design for great earthquakes,

b. California NEHRP Map Areas 3-6, Non-California Map Area 7 (parts of Alaska, Nevada, Idaho, Montana, and Wyoming), and Puget Sound NEHRP Map Area 5, which we take to be the only regions of the United States with a significant history of lifeline seismic design for major (as opposed to great) earthquakes, and

c. All other parts of the United States, which we assume have not had a significant history of lifeline seismic design for major earthquakes.

The two key quantitative vulnerability-function relationships developed under this project--*motion-damage curves* and *restoration curves*--define expected lifeline performance for each of these regions and form the heart of the quantitative vulnerability analysis. The curves are based on the data and methodology developed on the basis of expert opinion in the ATC-13 project (*Earthquake Damage Evaluation Data for California*, ATC 1985). Because the ATC-13 data and methodology are applicable for California structures only, however, the data were revised and reformatted to reflect differences in seismic design and construction practices nationwide and to meet the technical needs of the project. All assumptions operative in ATC-13, such as unlimited resources for repair and restoration, also apply to these results.

The *motion-damage curves* developed under this project define estimated lifeline direct damage as a function of seismic intensity (in this case, Modified Mercalli Intensity); direct damage is estimated in terms of repair costs expressed as a fraction or percentage of value. Curves are provided for each region defined above. An example set of motion-damage curves for ports/cargo handling equipment is provided in Figure 4.

The *restoration curves* developed for this project define the fraction of initial capacity of the lifeline (restored or remaining) as a function of elapsed time since the earthquake. Again curves are defined for each region. A sample set is provided in Figures 5 and 6.

4. Seismic Hazard

Seismic hazard, as used in this study, is the expectation of earthquake effects. It is usually defined in terms of ground shaking parameters (e.g., peak ground acceleration, Modified Mercalli Intensity, peak ground velocity) but, broadly speaking, can include or be defined in terms of fault rupture, ground failure (landslides, liquefaction), or other phenomena (earthquake-induced fire) resulting from an earthquake. Seismic hazard is a function of the size, or magnitude of an earthquake, distance from the earthquake, local soils, and other factors, and is independent of the buildings or other items of value that could be damaged.

The technical approach for evaluating the seismic hazard of lifeline structures in this project (see Chapter 4) involved identifying (1) the most appropriate means (parameter(s)) for describing the seismic hazard, (2) regions of high seismic activity, (3) representative potentially damaging, or catastrophic,

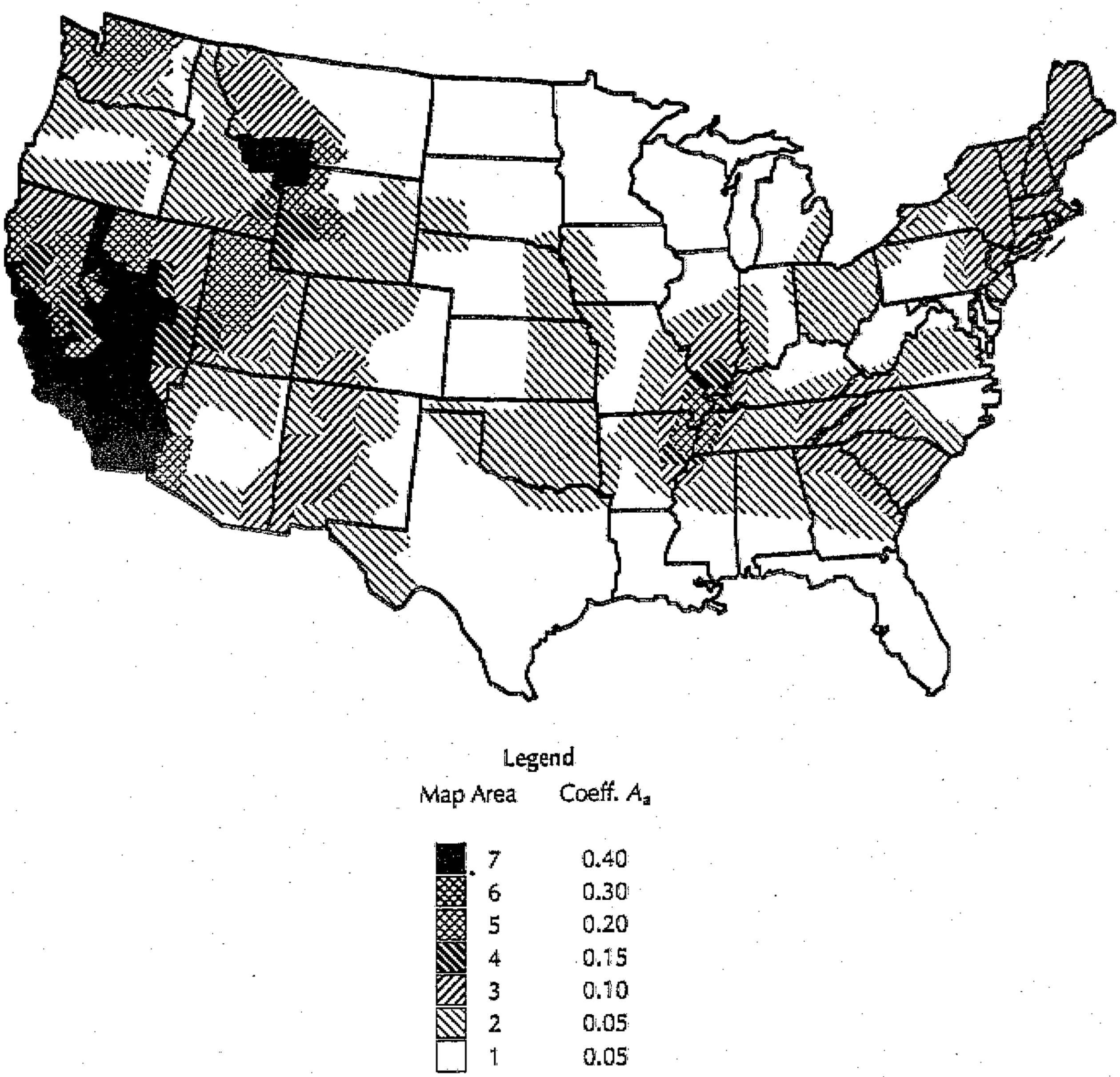


Figure 3 *NEHRP Seismic Map Areas (ATC, 1978; BSSC, 1988).*

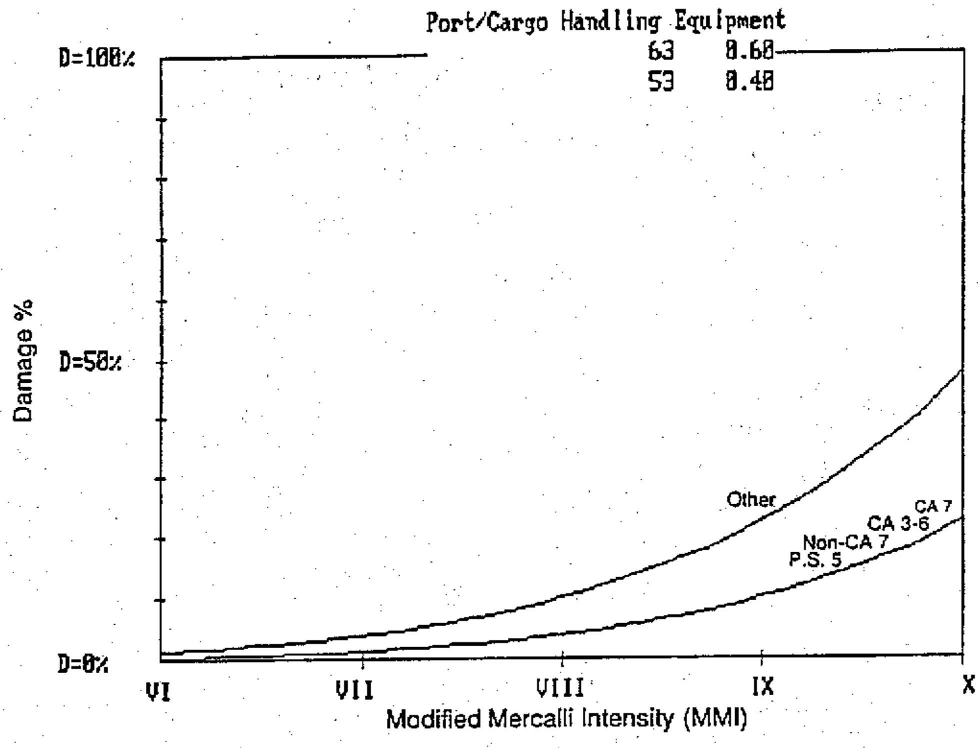


Figure 4 *Damage percent by intensity for ports/cargo handling equipment.*

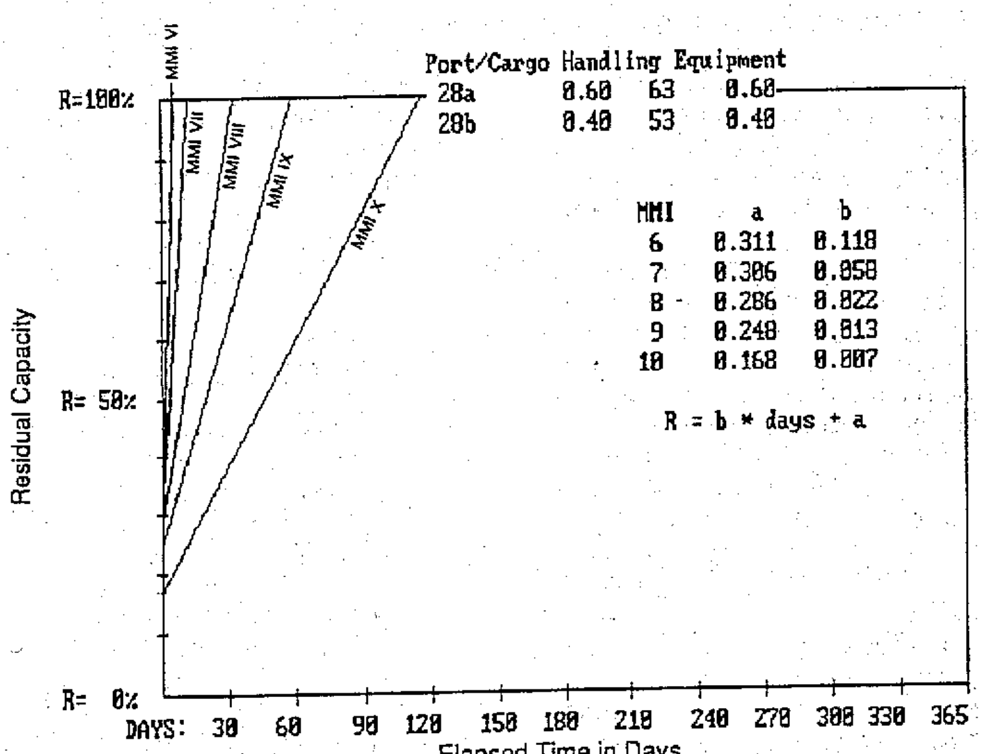


Figure 5 *Residual capacity for ports/cargo handling equipment (NEHRP Map Area: California 3-5, California 7, Non-California 7, and Puget Sound 5).*

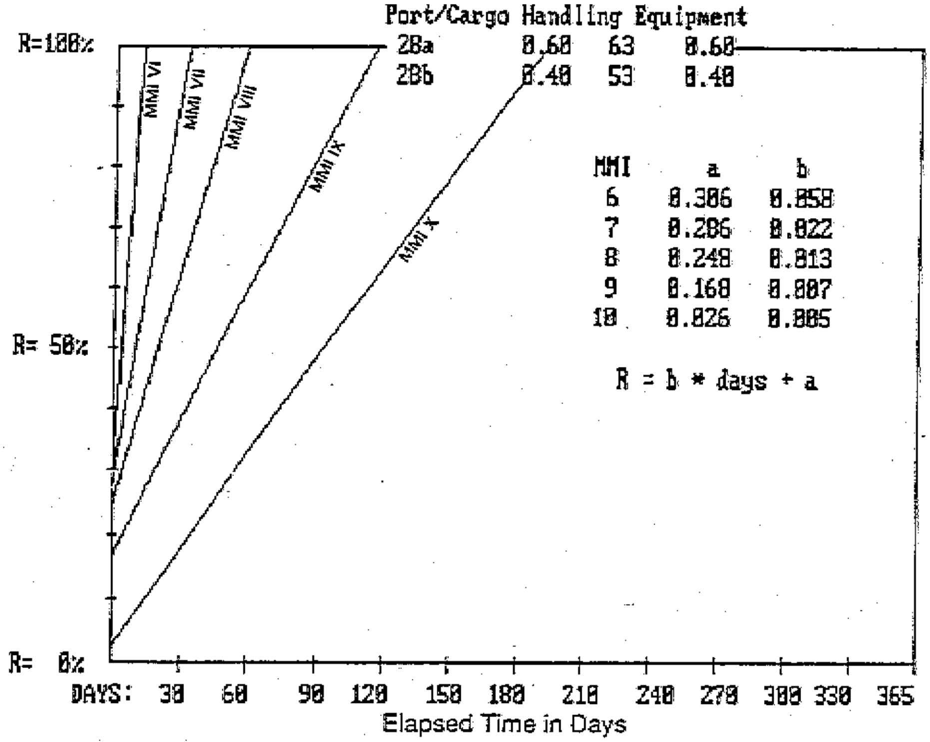


Figure 6 *Residual capacity for ports/cargo handling equipment (all other areas).*

earthquakes within each of these regions that could be used as scenario events for the investigation of lifeline loss estimation and disruption, and (4) a model for estimating the seismic hazard for each of these scenario events.

Descriptor of Seismic Hazard for this Study. Following a review of available parameters for characterizing seismic hazard, we elected to use the Modified Mercalli Intensity (MMI) Scale (Wood and Neumann, 1931), a commonly used measure of seismic intensity (effects at a particular location or site). The scale consists of 12 categories of ground motion intensity, from I (not felt, except by a few people) to XII (total damage). Structural damage generally is initiated at about MMI VI for poor structures, and about MMI VIII for good structures. MMI XI and XII are extremely rare. The MMI scale is subjective; it is dependent on personal interpretations and is affected, to some extent, by the quality of construction in the affected area. Even though it has these limitations, it is still useful as a general description of damage, especially at the regional level, and for this reason was used in this study as the descriptor of seismic hazard.

Seismicity Overview of the United States. For the purpose of characterizing seismicity in the conterminous United States, several regions may be identified (Algermissen, 1983):

1. Northeastern Region, which includes New England, New York, and part of eastern Canada;

2. Southeastern Region, including the central Appalachian seismic region activity and the area near Charleston, South Carolina;

3. Central Region, which consists of the area between the regions just described and the Rocky Mountains;

4. Western Mountain Region, which includes all remaining states except those on the Pacific coast;

5. Northwestern Region, including Washington and Oregon; and

6. California and Western Nevada.

The historical record indicates that each region appears to have significant historic precedent for a damaging earthquake of potentially catastrophic dimensions. For purposes of examining this potential, the earthquakes indicated in Table 1 are representative events for the investigation of lifeline loss estimation and disruption.

Evernden et al. (1981) estimates that these events represent almost the maximum earthquake expected in each area. Review of Algermissen et al. (1982) indicates general agreement.

Choice of a Model for Estimating the Distribution and Intensity of Shaking for Scenario Earthquakes. In order to estimate the seismic hazard (i.e., deterministic intensity) of the scenario events over the affected area associated with each event, a model of earthquake magnitude, attenuation, and local site effects is required. For the conterminous United States, two general models were considered: Evernden and Thomson (1985), and Algermissen et al. (1990).

Selection of one model over the other was difficult, but the Evernden model offered the following advantages for this study: (i) verification via comparison with historical events, (ii) incorporation of local soil effects and ready availability of a nationwide geologic database, and (iii) ready availability of closed-form attenuation relations. An important additional attribute for this project was that the Everden model would estimate the distribution and intensity of seismic shaking in terms of MMI, the shaking characterization used in the ATC-13 study and the basic parameter for the ATC-25 lifeline vulnerability functions.

Scenario Earthquakes. Based on the representative earthquakes identified in Table 1, which are considered representative of all major regions of the conterminous United States, eight scenario events were selected for this investigation. The eight events are indicated in Table 2. With the exception of the Cape Ann, Charleston, and Hayward events, all magnitudes are reflective of the representative earthquake for the region (as specified in Table 1). The scenario events for Cape Ann, Charleston, and Hayward have magnitudes one-half unit higher than the representative event. These magnitudes are interpreted as maximum credible for these locations.

Table 1 Representative Earthquakes for Lifeline Loss Estimation

Region	Event
Northeastern	Cape Ann, 1755
Southeastern	Charleston, 1886
Central	New Madrid, 1811-1812
Western Mountain	Wasatch Front, no date
Northwestern	Puget Sound, 1949
Southern California	Fort Tejon, 1857
Northern California	Hayward, 1868

The choice of a scenario event on the Hayward fault for the San Francisco Bay Area, rather than the 1906 San Francisco event, is based on the perceived high likelihood of a magnitude 7.0 event (USGS, 1990) as well as the potential for major damage and lifeline disruption, should such an event occur (CDMG, 1987). Since most lifelines approach San Francisco Bay from the east, more of them cross the Hayward Fault than cross the San Andreas Fault. So the Hayward event would appear to represent as disruptive an event, and potentially more so, than the 1906 event, which is presently perceived to be of low likelihood in the near future.

The Evernden model was employed to generate expected seismic intensity distribution in the conterminous United States for the eight scenario events. Shown in Figure 8 is an example intensity distribution for the New Madrid magnitude-8.0 scenario event.

Table 2 Scenario Earthquakes

Region	Event	Magnitude
Northeastern	Cape Ann	7
Southeastern	Charleston	7.5
Central	New Madrid	7 and 8
Western Mountain	Wasatch Front	7.5
Northwestern	Puget Sound	7.5
Southern California	Fort Tejon	8
Northern California	Hayward	7.5

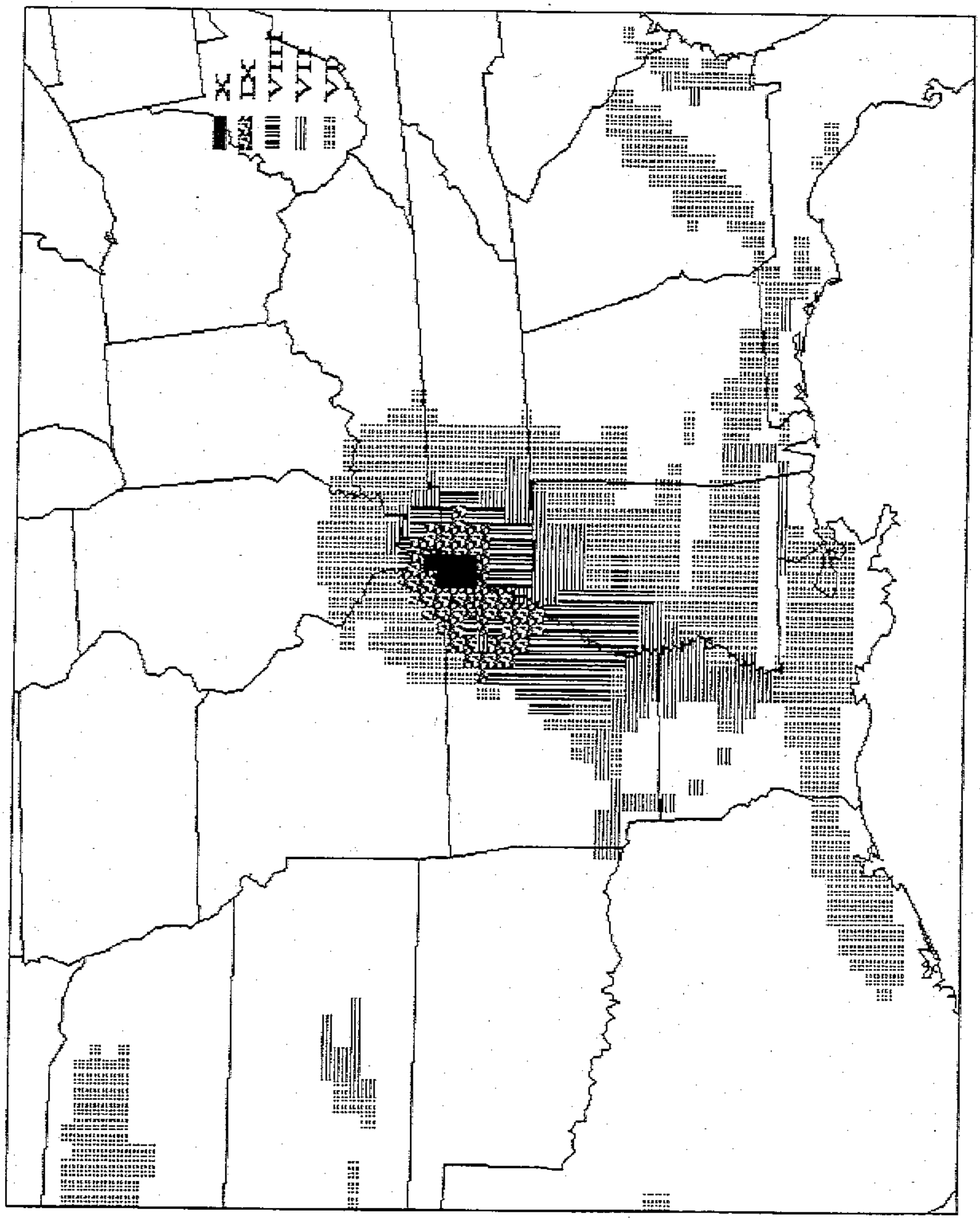


Figure 7 *Predicted intensity map for New Madrid (Magnitude 8).*

5. Estimates of Direct Damage

The analysis of seismic vulnerability of lifeline systems and the economic impact of disruption is based on an assessment of three factors:

- Seismic hazard,
- Lifeline inventory, and
- Vulnerability functions.

In this investigation these factors are used to quantify vulnerability and impact of disruption in terms of (1) direct damage and (2) economic losses resulting from direct damage and loss of function of damaged facilities. Estimates of direct damage to lifelines, expressed in terms of percent replacement value and dollar loss, are discussed in Chapter 5. Indirect economic losses are discussed in Chapter 6.

Direct damage is defined as damage resulting directly from ground shaking or other collateral loss causes such as liquefaction. For each facility, it is expressed in terms of cost of repair divided by replacement cost and varies from 0 to 1.0 (0% to 100%). In this project it is estimated using (1) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), (2) inventory data specifying the location and type of facilities affected (from Chapter 2), and (3) vulnerability functions that relate seismic intensity and site conditions to expected damage (from Chapter 3 and Appendix B).

The analysis approach to estimate direct damage considers both damage resulting from ground shaking as well as damage resulting from liquefaction. Damage due to other collateral loss causes, such as landslide and fire following earthquake, are not included because of the unavailability of inventory information and the lack of available models for estimating these losses nationwide.

The analysis approach for computing direct damage due to ground shaking proceeded as follows. For each earthquake scenario, MMI levels were assigned to each 25-km grid cell in the affected region, using the Everden MMI model, assigned magnitude, and assigned fault rupture location (from Chapter 4). Damage states were then estimated for each affected lifeline component in each grid cell, using the motion-damage curves provided in Appendix B. The procedure for utilizing the motion-damage curves varied slightly by facility type, depending on whether the lifeline was a site specific facility, or a regional transmission (extended) network.

Site-Specific Lifelines. Direct damage to site-specific lifelines, i.e., lifelines that consist of individual sited or point facilities (e.g., hospitals), were estimated using the methodology specified above. For airports, ports and harbors, medical care facilities (hospitals), and broadcast stations, the inventory data summarized in Chapter 2 were used to define the number and distribution of facilities. For fire and police stations, locations were assumed to be lumped at the center of the Standard Metropolitan Statistical Areas, and number of facilities affected were estimated by proxy, assuming certain established relationships between population and number of facilities.

For summary and comparative purposes, four damage states are considered in this study:

- Light damage (1-10% replacement value);
- Moderate damage (10-30% replacement value);
- Heavy damage (30-60% replacement value); and
- Major to destroyed (60-100% replacement value).

The total number of affected facilities and the percentage of facilities in each damage state are summarized for each lifeline and scenario earthquake (see Chapter 5, Tables 5-1 through 5-6). Following is a discussion of the direct damage impact on an example lifeline--ports and harbors.

<u>Ports and Harbors</u>. Since ports and harbors are located in the coastal regions, only those scenario earthquakes affecting these regions will negatively impact this facility type. As indicated in Table 3, the most severe damages to ports and harbors are expected for the Charleston and Puget Sound events. For example, one hundred percent, or 20 ports and harbors, in South Carolina can be expected to sustain heavy damage (30 to 60%), and 73%, or approximately

Table 3 **Damage Percent for Ports and Harbors for Selected Scenario Earthquakes (Percent of Ports and Harbors in State)**

CAPE ANN (M=7.0)

Massachusetts 34	*Connecticut* 22	*Delaware* 10	*Rhode Island* 22	*New Hampshire* 9
100%	0%	0%	86%	0%
0%	0%	0%	0%	0%
0%	0%	0%	0%	0%
0%	0%	0%	0%	0%

CHARLESTON (M=7.5)

Total Number	*South Carolina* 20	*North Carolina* 16	*Georgia* 30
Light Damage 1-10 %	0%	0%	10%
Moderate 10-30 %	0%	0%	0%
Heavy 30-60 %	100%	0%	73%
Major to Destructive 60-100 %	0%	0%	0%

	HAYWARD (M=7.5)	*FORT TEJON (M=8.0)*	*PUGET SOUND (M=7.5)*
Total Number	*California* 125	*California* 125	*Washington* 77
Light Damage 1-10 %	4%	0%	25%
Moderate 10-30 %	22%	34%	26%
Heavy 30-60 %	0%	0%	14%
Major to Destructive 60-100 %	0%	0%	0%

22 such facilities would be similarly affected in Georgia. In Washington, 14% of the ports (approximately 11) would be similarly affected. Numerous ports and harbors in these states would also sustain moderate damage (10 to 30%), as would approximately 22 such facilities in California for the Hayward magnitude-7.5 event. The primary cause of such damage, of course, is poor ground.

Extended Lifeline Networks. With the exception of pipeline systems, direct damage to extended network lifelines, such as highways, railroads and other networks at the bulk and/or regional level, was estimated using the methodology specified above. For pipelines direct damage was estimated using an analytical model that estimates the probability of breaks occurring within given lengths of pipe subjected to given earthquake shaking intensities (Khater et al., 1989).

Results are presented in terms of (1) the same four damage states used for site-specific lifelines, and (2) maps indicating the damaged portions of each extended network for the various scenario earthquakes (see Chapter 5). Example results for two extended lifeline networks follow.

Railroad System. The railroad system is a highly redundant system, and damage to the system due to the selected events was found to be relatively localized to the epicentral area. Direct damage estimates for the railroad system are based on damage curves for track/roadbed and exclude damage to related facility types not included in the project inventory--railway terminals, railway bridges and tunnels.

The direct damage data (Chapter 5, Table 5-7) suggest that the magnitude-8 New Madrid, Fort Tejon, and Hayward events would cause the most extensive damage, with 2,265 km, 872 km, and 585 km of roadbed, respectively, sustaining damage in the 30 to 100% range. Damage in the Charleston, Puget Sound, and magnitude-7.0 New Madrid events would also be severe, with 980, 650, and 640 km of roadbed, respectively, sustaining heavy damage (30-to-60 %). A map showing the distribution of damage to the railroad system for the magnitude-8 New Madrid earthquake scenario is shown in Figure 8.

Crude Oil. Direct damage to the crude oil system as a result of the magnitude-8 New Madrid event, estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines, is plotted in Figure 9. This figure indicates that three pipeline sections would be damaged due to the magnitude-8.0 New Madrid event and suggests that crude oil flow to the north-central section of the United States would be disrupted. Pipelines would also be damaged as a result of the magnitude-7 New Madrid and magnitude-8 Fort Tejon earthquake scenarios.

Dollar Loss Estimates. Summaries of dollar loss estimates for direct damage to site-specific systems and extended regional lifeline networks during the eight scenario earthquakes are provided in Tables 5a and 5b. Estimated dollar losses due to direct damage to local electric, water, and highway distribution systems are provided in Table 6.

The estimates provided in Tables 5a,b and 6 are based on the available inventory data, cost per facility assumptions, and other models and assumptions described throughout the report. As a result, the accuracy of these estimates may vary from lifeline to lifeline. Estimates for electric systems, in particular, are believed to be more sensitive to the lack of capacity information than are the other lifelines.

By combining the data from Tables 5a,b and 6, we estimate the total direct damage dollar losses (in billions of U. S. dollars) for the eight scenario earthquakes as follows:

Earthquake	*Direct Dollar Loss (in Billions, 1991$)*
Cape Ann	$4.2
Charleston	$4.9
Fort Tejon	$4.9
Hayward	$4.6
New Madrid, M = 8.0	$11.8
New Madrid, M = 7.0	$3.4
Puget Sound	$4.4
Wasatch Front	$1.5

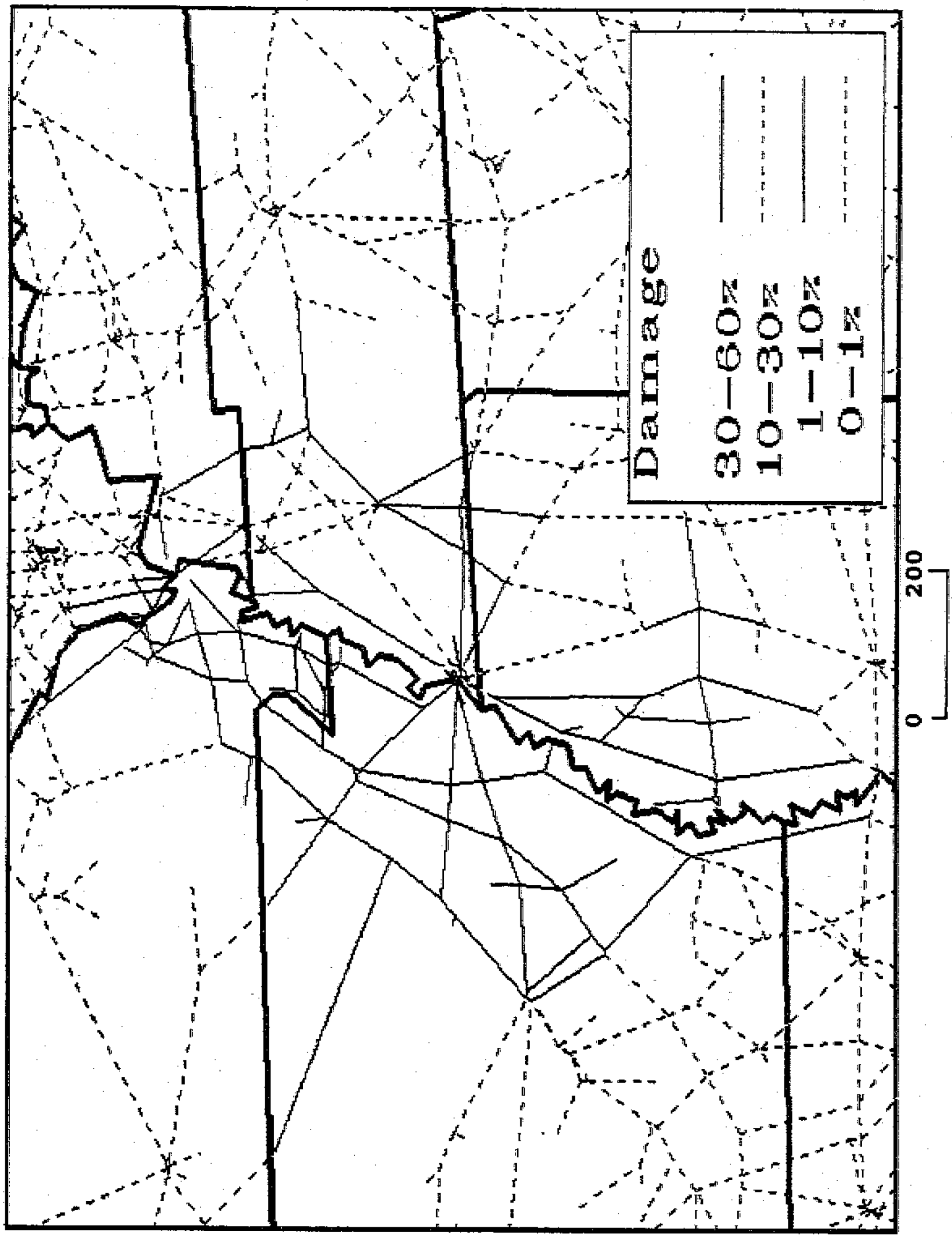


Figure 8 *Damage to railroad system following magnitude-8 New Madrid Event.*

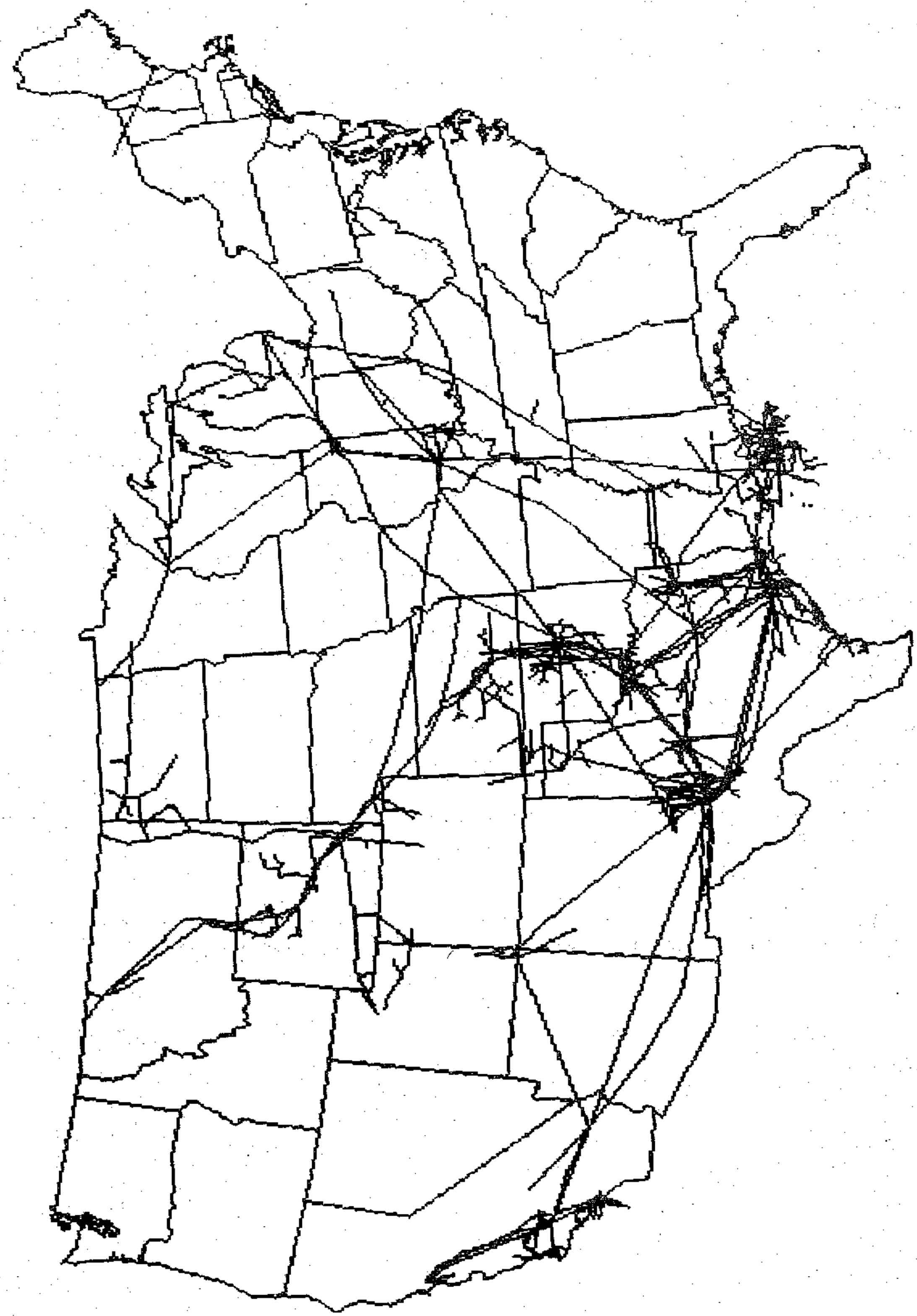


Figure 9 *Damage to crude oil system following magnitude-8 New Madrid Event. Broken pipelines are shown in red; unbroken pipelines are shown in black.*

Table 5a **Direct Damage Losses to Site-Specific Lifelines ($ Millions)**

Scenario Earthquake	*Airports*	*Ports*	*Hospitals*	*Broadcast Stations*	*Fire Stations*
Cape Ann	$91	$53	$490	$19	$6
Charleston	142	380	565	68	9
Fort Tejon	148	170	1,431	26	48
Hayward	37	115	1,297	17	7
New Madrid (M=8)	411	0	1,297	91	13
New Madrid (M=7)	145	0	396	34	3
Puget Sound	210	196	507	49	13
Wasatch Front	29	0	205	44	2

Table 5b **Direct Damage Losses to Regional Network Lifelines ($ Millions)**

Scenario Earthquake	*Highways*	*Electric*	*Railroads*	*Natural Gas*	*Refined Oil*	*Crude Oil*	*Water*
Cape Ann	$382	$1,312	$9	$0	$0	$0	$0
Charleston	773	1,264	156	0	0	0	0
Fort Tejon	470	886	158	11	0	28	140
Hayward	208	1,310	115	6	0	0	91
New Madrid (M=8)	2,216	2,786	458	56	28	47	0
New Madrid (M=7)	204	1,077	108	19	9	19	0
Puget Sound	496	1,834	96	6	0	0	18
Wasatch Front	323	90	31	6	0	0	0

Table 6 **Direct Damage Losses to Local Distribution Systems**

Event	*Electric $ Billion*	*Water $ Billion*	*Highways $ Billion*
Cape Ann	$0.89	$0.30	$0.60
Charleston	0.74	0.31	0.50
Fort Tejon	0.91	0.23	0.23
Hayward	0.90	0.20	0.25
New Madrid (M=8.0)	2.07	0.88	1.40
New Madrid (M=7.0)	0.65	0.28	0.44
Puget Sound	0.58	0.09	0.28
Wasatch Front	0.38	0.13	0.26

6. Estimation of Indirect Economic Effects

Earthquakes produce both direct and indirect economic effects. The direct effects, such as dollar loss due to fires and collapsed structures, are obvious and dramatic. However, the indirect effects that these disruptions have on the ability of otherwise undamaged enterprises to conduct business may be quite significant. Although the concept of seismic disturbances and their effect on lifelines has been investigated for at least two decades, there is very little literature on indirect economic losses.

This study provides a first approximation of the indirect economic effects of lifeline interruption due to earthquakes. To accomplish this the relevant literature was surveyed. Then a methodology was developed to relate lifeline interruption estimates to economic effects of lifeline interruption in each economic sector. This required a two-step process:

1. Development of estimates of interruption of lifelines as a result of direct damage

2. Development of estimates of economic loss as a result of lifeline interruption

Estimates of Lifeline Interruption. Lifeline interruption resulting from direct damage is quantified in this investigation in residual capacity plots that define percent of function restored as a function of time. The curves are estimated for each lifeline type and scenario earthquake using (1) the time-to-restoration curves discussed in Chapter 3 and provided in Appendix B, (2) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), and (3) inventory data specifying the location and type of facilities affected (from Chapter 2).

For site-specific systems (i.e., lifelines consisting of individual sited or point facilities, such as airports or hospitals) the time-to-restoration curves are used directly whereas for extended regional networks, special analysis procedures are used. These procedures consist of:

- connectivity analyses, and

- serviceability analyses.

Connectivity analyses measure post-earthquake completeness, "connectedness," or "cut-ness" of links and nodes in a network. Connectivity analyses ignore system capacities and seek only to determine whether, or with what probability, a path remains operational between given sources and given destinations.

Serviceability analyses seek an additional valuable item of information: If a path or paths connect selected nodes following an earthquake, what is the remaining, or residual, capacity between these nodes? The residual capacity is found mathematically by convolving lifeline element capacities with lifeline completeness.

A complete serviceability analysis of the nation's various lifeline systems, incorporating earthquake effects, was beyond the scope of this project. Additionally, capacity information was generally not available for a number of the lifelines (e.g, for the highway system, routes were available, but not number of lanes). Rather, for this project, a limited serviceability analysis has been performed, based on a set of simplifying assumptions.

The fundamental assumption has been that, on average, all links and nodes of a lifeline have equal capacities, *so that residual capacity has been determined as the ratio of the number of serviceable (i.e., surviving) links and nodes to the original number of serviceable links and nodes, for a given source/destination pair, or across some appropriate boundary*. For example, if the state of South Carolina has 100 airports, and 30 of these are determined to be unserviceable at some point in time following a major earthquake, then the air transport lifeline residual capacity is determined to be 70% of the initial capacity.

An example illustrating the residual capacity plots for one lifeline and their implication is discussed below. Included in Chapter 6 are example residual capacity plots for all lifelines considered. Appendix C contains all residual capacity plots developed under this project (for the various lifelines and scenario earthquakes).

Ports. An example residual capacity plot for South Carolina, the worst-case situation, is provided in Figure 10. In this example, the initial loss is nearly 100 percent of capacity, and full

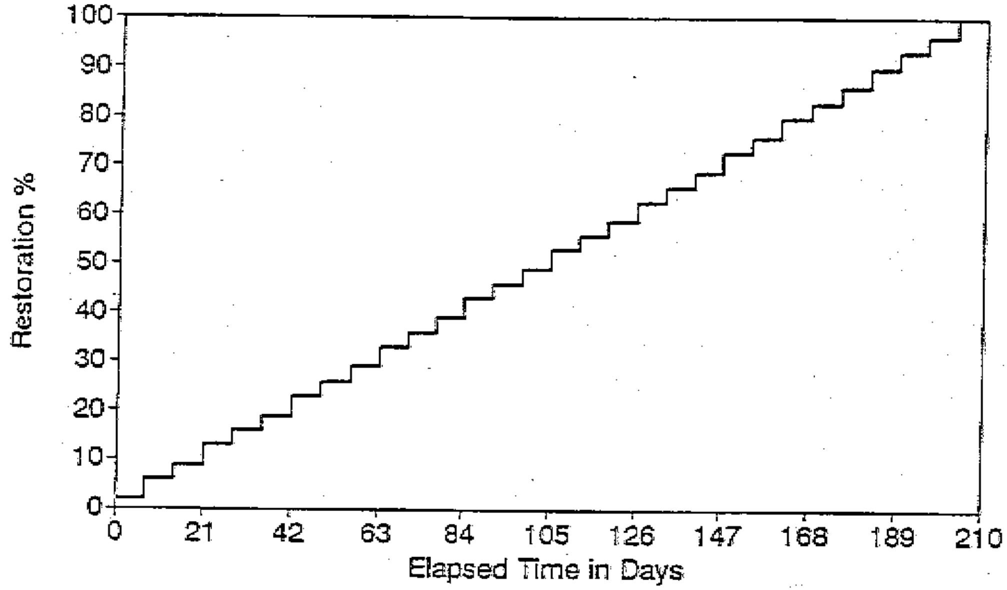


Figure 10 *Residual capacity of South Carolina ports following Charleston event (M=7.5).*

capacity is not restored until about day 200. Georgia would also experience similarly high losses due to the Charleston event. Massachusetts and Rhode Island would experience the largest losses due to the Cape Ann event.

Estimates of Indirect Economic Losses. Economic activity within each industrial sector was measured in terms of value added. Value added refers to the value of shipments (products) less the cost of materials, supplies, contract work and fuels used in the manufacture or cultivation of the product. The United States Bureau of Economic Analysis publishes annual data for value added for each industrial sector. For simplicity, data from the 99 sectors were collapsed into 36 sectors. Data for 1983 were the latest available (published by BEA, 1989), and were used in this study.

Reduction in Value Added Due to Lifeline Interruption. Table 7 presents the percent reduction in value added for each sector resulting from increasingly severe crude oil lifeline interruptions. (Similar tables are shown for all lifelines in Appendix D.) Values are shown for each decile of lifeline interruption and are assumed to pertain to *monthly* Gross National Product (GNP).

Indirect Economic Loss Results. Indirect economic losses were estimated for each lifeline system and scenario event using the residual capacity plots provided in Appendix C and the economic tables described above. The calculation procedure are described in Chapter 6.

Summaries of the total indirect economic losses resulting from damage to site-specific systems and extended regional networks, based on 1986 GNP data, are provided in Table 8. Total indirect economic losses resulting from damage to local distribution systems are presented in Table 9. We note that Table 8 contains total loss amounts expressed in terms of lower bound, upper bound, and best estimate. The lower bound represents economic loss caused by the singular lifeline system causing the greatest loss; the upper bound is the sum of losses caused by all systems; and the best estimate is the square root of the sum of the squares (SRSS) of losses

Table 7 Percent Value-Added Lost Due to Specified Percent Loss of Oil Supply Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
2 Agr. Prod.	1.06%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
3 AgServ For. Fish	0.11%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
4 Mining	3.89%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
5 Construction	5.52%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
6 Food Tobacco	2.41%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
7 Textile Goods	0.37%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
8 Misc Text. Prod.	0.73%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
9 Lumber & Wood	0.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
10 Furniture	0.34%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
11 Pulp & Paper	0.87%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
12 Print & Publish	1.31%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
13 Chemical Drugs	1.40%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
14 Petrol. Refining	0.96%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
15 Rubber & Plastic	1.03%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
16 Leather Prods.	0.12%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
17 Glass Stone Clay	0.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
18 Prim. Metal Prod.	1.04%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
19 Fab. Metal Prod.	1.64%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
20 Mach. Exc. Elec.	1.56%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
21 Elec. & Electron	2.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
22 Transport Eq.	2.62%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
23 Instruments	0.68%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
24 Misc. Manufact.	0.69%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
25 Transp & Whse.	3.46%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
26 Utilities	5.89%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
27 Wholesale Trade	5.63%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
28 Retail Trade	5.63%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
29 F.I.R.E.	16.64%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
30 Pers./Prof. Serv.	8.03%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
31 Eating Drinking	2.12%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
32 Auto Serv.	1.09%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
33 Amuse & Rec.	0.70%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
34 Health Ed. Soc.	6.30%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
35 Govt & Govt Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
TOTAL	100.00%	3.25% Avg.	9.74% Avg.	16.23% Avg.	22.72% Avg.	29.21% Avg.	35.70% Avg.	42.19% Avg.	48.68% Avg.	55.18% Avg.	61.67% Total V.A Pct. V.A.

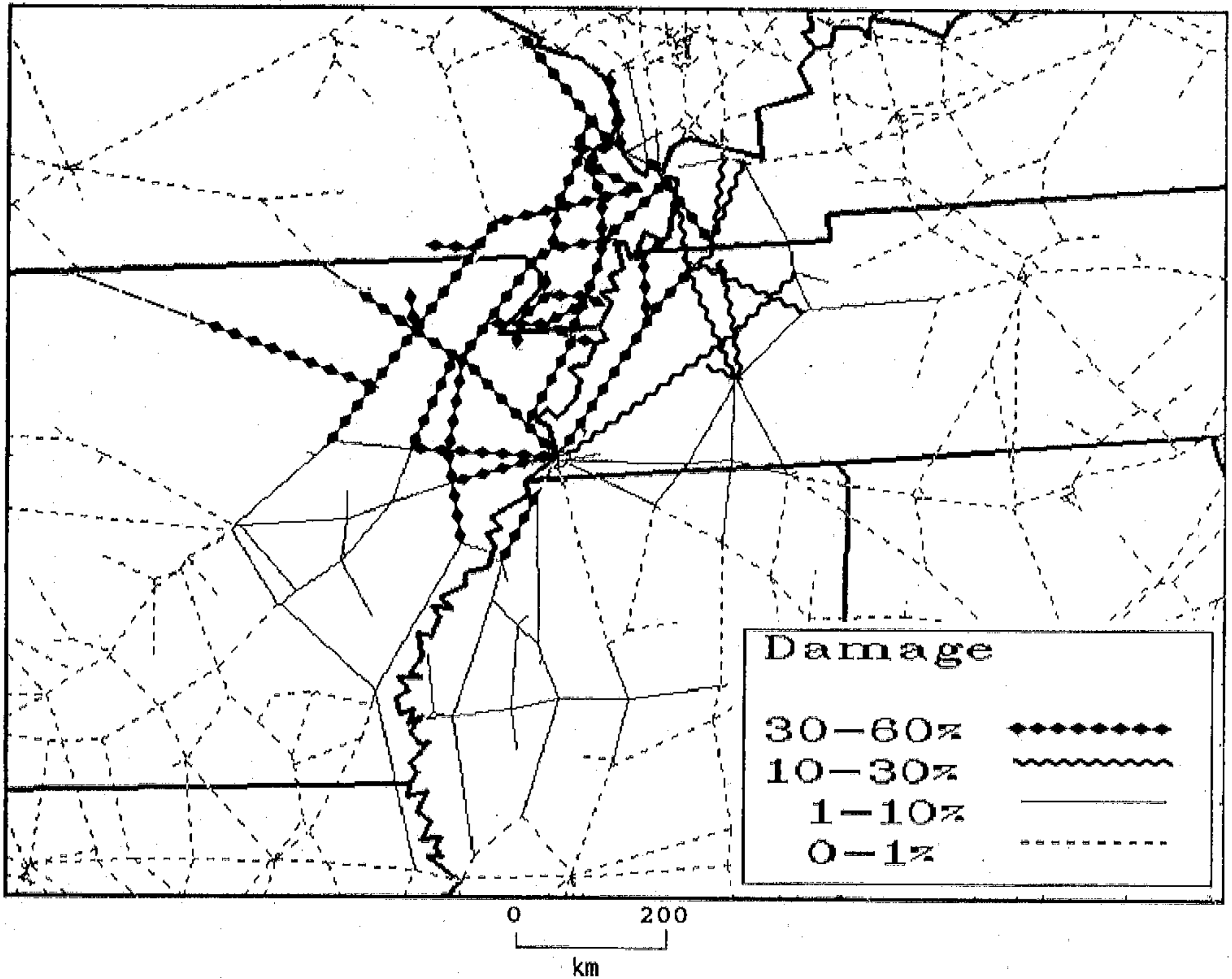


Figure 16 *Damage to railroad system following magnitude-8 New Madrid Event.*

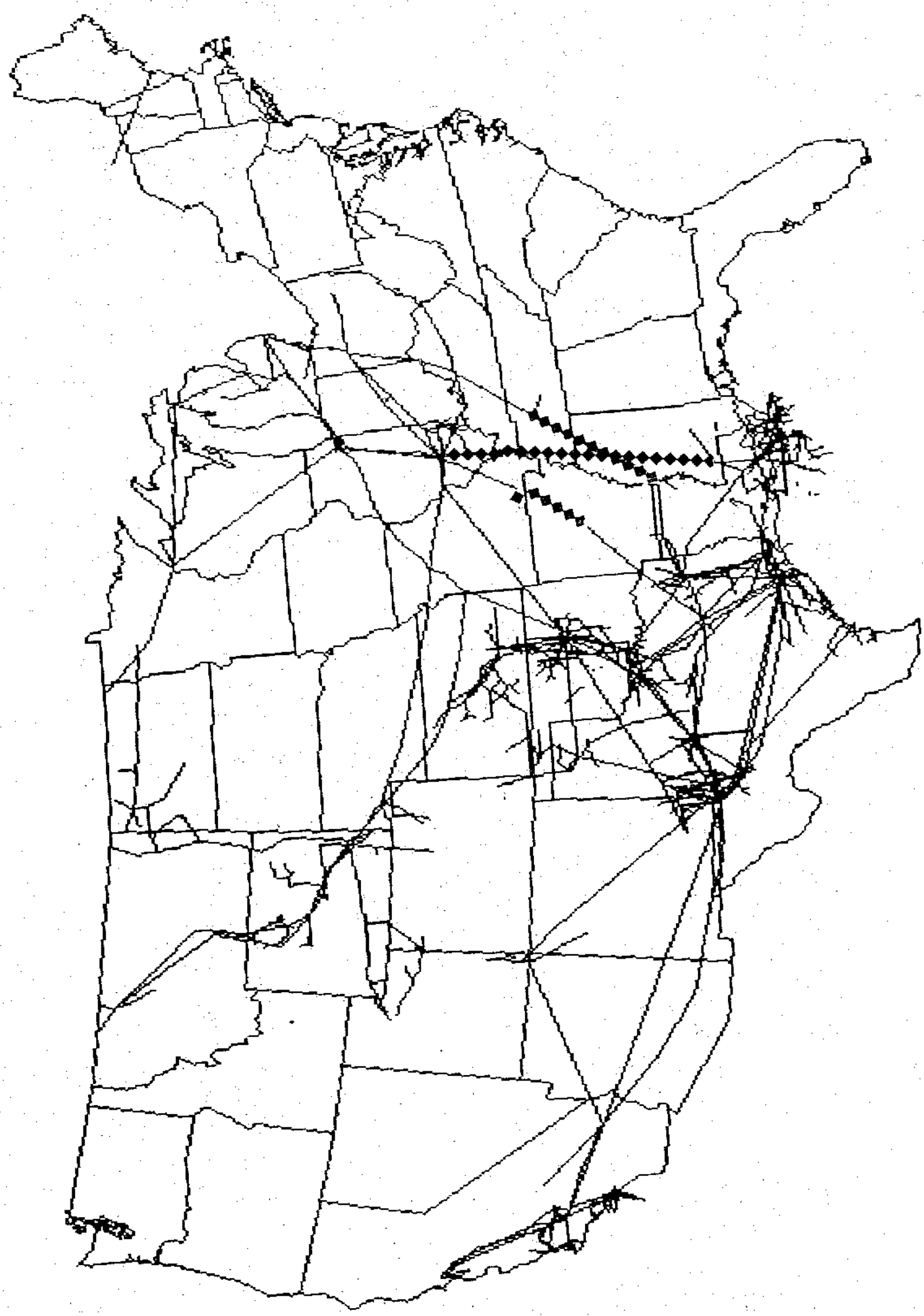


Figure 17 *Damage to crude oil system following magnitude-8 New Madrid Event. Broken pipelines are shown with solid diamonds.*

caused by each lifeline. We note also that the SRSS procedure was used to estimate total indirect economic losses resulting from damage to local distribution networks (Table 9).

By combining like system data from Tables 8 and 9 in a least squares (SRSS) fashion, we estimate the total indirect economic losses for the eight scenario earthquakes as follows:

Earthquake	*Indirect Loss (in Billions, 1991$)*
Cape Ann	$9.1
Charleston	$10.2
Fort Tejon	$11.7
Hayward	$11.1
New Madrid, M = 8.0	$14.6
New Madrid, M = 7.0	$4.9
Puget Sound	$6.1
Wasatch Front	$3.9

Bar charts showing the indirect losses caused by transmission lines (upper bound data) by state for each scenario earthquake were also developed. An example plot for the magnitude-8 New Madrid scenario event is provided in Figure 11. We note that estimates of indirect economic losses for each state are sensitive to the assumed location of the source zone for large-magnitude events (e.g., had the assumed source zone for the magnitude-8 New Madrid event been located further north, estimates of direct damage in Missouri would have been substantially larger).

The data provided in Figure 11 suggests Mississippi and Arkansas would experience the highest indirect losses due to the magnitude-8.0 New Madrid event. Similar plots for the other scenario earthquakes (Chapter 6) indicate that: Massachusetts would experience the highest indirect losses due to the Cape Ann event with the electric system contributing the highest portion; and South Carolina, Utah, Washington, Northern and Southern California would experience the highest indirect losses due to the Charleston, Utah, Seattle, Hayward, and Fort Tejon events, respectively. The electric system contributes the highest indirect losses, among all systems, for most of the events.

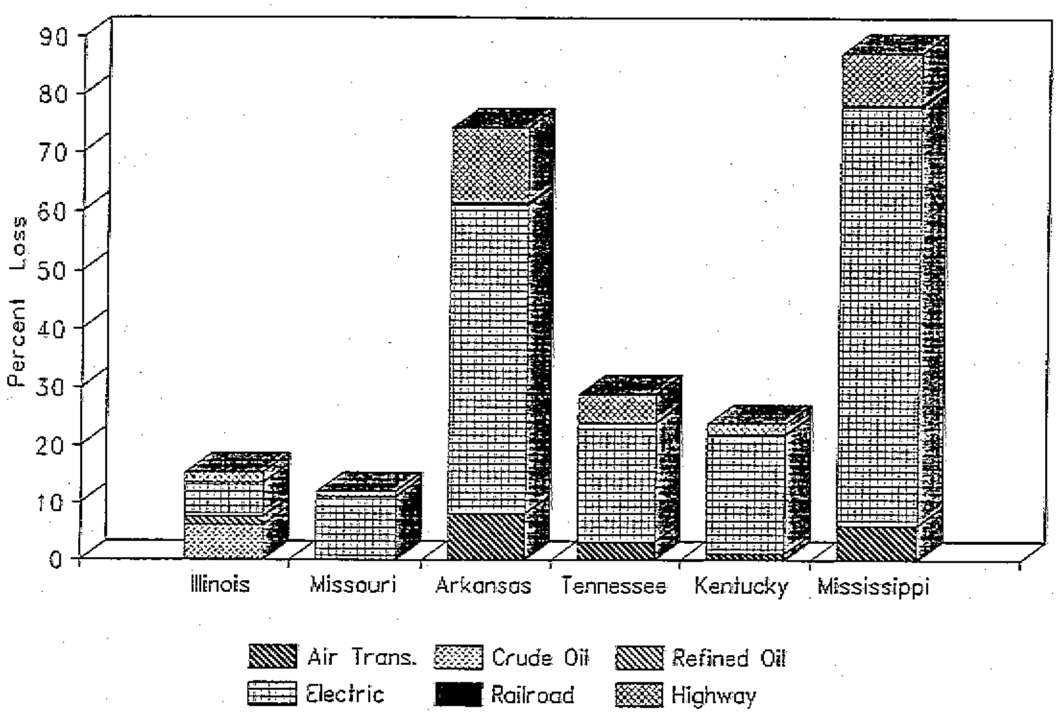


Figure 11 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, New Madrid event (M=8.0). Note that the relatively low losses for Missouri reflect the assumed location of the scenario earthquake source zone and the estimated distribution of intensity (see Figure 7).*

7. Combined Economic Losses, Deaths and Injuries

Human Death and Injury. It is generally felt that lifeline performance and continuity of operation is vital to human survival in the modern, urban, world. Most observers believe that damage to lifelines would result in human death and injury. Analogous to direct damage to property and indirect economic losses, human death and injury resulting from lifeline damage can be categorized as follows:

1. Human death and injury caused by lifeline functional curtailment, where persons suffer as a result of deprivation of vital services; and

2. Human death and injury resulting from direct damage to lifelines (e.g., occupant injuries resulting from the collapse of an air terminal building).

Casualties Due to Lifeline Functional Curtailment. Without the benefit of hard data it is difficult to estimate with high confidence the number of casualties that will result from curtailment of lifeline function. Our preliminary assessment is that human death and injury due to functional curtailment of lifelines can generally be expected to be very low. This is a fundamental assumption of this study, and will probably cause some debate. Each lifeline was considered, and this conclusion was found to hold, based on the following assumptions: (1) most vital installations that normally require a lifeline service have back-up emergency supplies, and (2) most lifelines have considerable elasticity in demand, and the level of service necessary for life maintenance is very low. Examples follow:

- Electricity. Persons can survive without power, even in the Northeast in the winter. Most hospitals and similar installations have emergency generators. Those that lack emergency generators can transfer patients to other sites.

- Water. Water for human survival is very minimal. Humans can survive without water for 48 or more hours, and water for human survival can be imported if necessary.

- Gas and Liquid Fuels. Gas and liquid fuel systems are probably the most critical of all lifelines, yet capacity is very elastic, and only short-term shortages are expected. Fuel for heating in the Northeast in the winter can be conserved if necessary by clustering people in school gymnasia, national guard armories, and so on.

- Rail, Air, and Highway Transportation. Transportation lifelines are highly redundant and thus very elastic; emergency food and medicines would be expected to be deliverable regardless of earthquake damage.

Casualties Resulting From Lifeline Direct Damage. Casualties can result from direct damage, especially catastrophic collapse, of lifeline components. Although few deaths occurred directly as a result of lifeline damage in U. S. earthquakes prior to 1989, life-loss due to lifeline failure was tragically demonstrated during the October 17, 1989, Loma Prieta, California, earthquake. Approximately two thirds of the 62 deaths from this earthquake resulted from the failure of a lifeline component--partial collapse of the Cypress structure, a double-decked highway viaduct in Oakland approximately 100 km from the earthquake source zone.

Although it can be argued that the deaths and injuries caused by lifeline failure in the Loma Prieta earthquake were the exception, not the rule, the vulnerability functions developed for this project suggest that substantial life-loss from lifeline component failure should be anticipated. Lifeline failures that could cause substantial life loss or injury include bridge failure, railroad derailment, and pipeline failure.

Unfortunately, data necessary for estimating life loss associated with these component failures are not readily available, precluding development of reliable casualty estimation methodology and data for lifeline structures.

Combined Direct and Indirect Economic Losses. Summaries of total dollar losses from direct damage and indirect economic losses are combined and summarized for each scenario earthquake and lifeline in Table 10. The total

Table 10 Total Direct Plus Indirect Dollar Losses for Each Scenario Earthquake and Lifeline (Billions of Dollars)

Scenario	*Electric*	*Highways*	*Water*	*Medical Care*	*Ports*	*Railroads*	*Airport*	*Natural Gas*	*Crude Oil*	*Refined Oil*	*Broadcasting Stations*	*Fire Stations*	*Total*
Cape Ann	$11.24	$2.06	$0.91	$0.49	$0.50	$0.03	$0.58	$0.00	$0.00	$0.00	$0.02	$0.01	$13.25
Charleston	$10.82	$2.05	$0.94	$0.57	$5.30	$0.18	$0.59	$0.00	$0.00	$0.00	$0.07	$0.01	$15.11
Fort Tejon	$9.66	$5.18	$5.27	$1.43	$2.65	$0.41	$1.57	$1.68	$4.38	$0.00	$0.03	$0.05	$16.58
Hayward	$12.21	$2.52	$4.38	$1.30	$1.46	$0.22	$0.44	$0.09	$0.00	$0.00	$0.02	$0.01	$15.66
New Madrid 8	$15.68	$13.19	$2.68	$1.30	$0.00	$0.71	$1.22	$0.34	$0.46	$0.23	$0.09	$0.01	$26.37
New Madrid 7	$5.17	$4.12	$0.85	$0.40	$0.00	$0.15	$0.31	$0.18	$0.13	$0.16	$0.03	$0.00	$8.29
Puget Sound	$8.29	$1.95	$0.90	$0.51	$0.73	$0.21	$0.62	$0.21	$0.00	$0.00	$0.05	$0.01	$10.48
Wasatch Front	$2.21	$3.85	$0.40	$0.20	$0.00	$0.05	$0.11	$0.04	$0.00	$0.00	$0.04	$0.00	$5.41

losses for each scenario earthquake are as follows:

Earthquake	Direct Plus Indirect Losses (in Billions, 1991$)
Cape Ann	$13.3
Charleston	$15.1
Fort Tejon	$16.6
Hayward	$15.7
New Madrid, M = 8.0	$26.4
New Madrid, M = 7.0	$8.3
Puget Sound	$10.5
Wasatch Front	$5.4

8. Hazard Mitigation of Critical Lifelines

Identification of Critical Lifelines. Based on the combined direct and indirect economic losses presented above and with due consideration of the assumptions and limitations expressed throughout this report, we offer the following relative ranking of the criticality of different lifelines in terms of the estimated impact of damage and disruption:

Rank	Lifeline	Event/Location
1.	Electric System	New Madrid (M=8.0)
		Hayward
		Cape Ann, Charleston, Fort Tejon
2.	Highways	New Madrid (M=8.0)
		Fort Tejon
		Hayward, New Madrid (M=7.0)
3.	Water System*	Fort Tejon
4.	Ports	Charleston
5.	Crude Oil	Fort Tejon

*The ranking for the water system may be underestimated because critical components such as pumping stations and dams were not included in the study.

Measures for Reducing Vulnerability of Lifeline Systems. The seismic vulnerability of lifeline systems, from the point of view of fulfilling function, can be reduced through three primary approaches:

1. Damage reduction measures. In this approach reliability of function is enhanced by reducing damage. This approach may take the form of :
   - Strengthening a building, bracing equipment, or performing other corrective retrofit measures to mitigate shaking effects;
   - Densifying the soil beneath a structure, or placing a structure on piles, or using other techniques to mitigate hazardous geotechnical conditions, e.g., liquefaction potential,
   - Other component improvements, depending on the component and potential earthquake impacts, e.g., replacement of vulnerable systems/components with new systems/components that will provide improved seismic resistance.
2. Provision for system redundancy. In this approach, reliability of function is enhanced by providing additional and alternative links (e.g., new highways, pipelines, other transmission or distribution links). Because earthquake damage is fundamentally a random phenomena, addition of system links will tend to increase system reliability.
3. Operational improvements. In this approach reliability of function is enhanced by providing emergency response planning and the capability to rapidly and effectively repair damage, redirect functions, or otherwise mitigate earthquake damage impacts on system operations and thereby re-establish system function.

Of these measures, the most common are component strengthening/retrofit measures, which are discussed at length in Appendix B of this report. The proposed measures (Appendix B) include generic solutions, such as designing structures to meet current seismic design or retrofit standards of the local community, or anchoring equipment. In addition, there are numerous specific measures that relate to unique systems or components within each lifeline. Special attention should be directed to those systems and conditions that are of greatest concern, such as porcelain components in electric substations.

Following are recommended steps when implementing a program to reduce seismic hazards of existing lifelines:

1. Review existing descriptions of seismic performance and rehabilitation measures for the lifeline(s) of concern, i.e., familiarize yourself and your organization with the overall problem. Sources include Appendix B and Chapter 10 (References) of this report.

2. Conduct an investigation of the seismic vulnerability and impact of disruption for the lifeline(s) and region(s) of concern. Lifeline seismic evaluation methodologies and other potential resources for this purpose have been developed by the ASCE Technical Council for Lifeline Earthquake Engineering (see references, Chapter 10), the Applied Technology Council (ATC, in preparation) and others.

3. Focus first on the most vulnerable lifelines, components, and conditions (e.g., liquefaction or landslide potential). Vulnerable components include:

   For electric systems:
   - Substations
   - Power stations

   For water systems:
   - Pumping stations
   - Tanks and reservoirs
   - Treatment plants
   - Transmissions aqueducts

   For highway systems
   - Bridges
   - Tunnels
   - Roadbeds

   For water transportation systems:
   - Port/cargo handling equipment
   - Inland waterways

   For gas and liquid fuels:
   - Distribution storage tanks
   - Transmission pipelines
   - Compressor, metering and pressure reduction stations

4. Conduct cost-benefit studies to determine the most cost effective measures. We note that, in some cases, retrofit measures may not be very cost effective. In regions where the return period for large earthquakes is quite long, for example, replacement over the life cycle of the facility or component may be a reasonable approach.

5. Implement the selected hazard reduction measures.

9. Recommendations for Further Work

The ATC-25 project has raised a number of questions and indicated areas in which knowledge is inadequate or nonexistent with respect to the impact of lifeline disruption due to earthquake. Following are recommendations for further research and other efforts. This list is not meant to be all inclusive but rather an overview of some of the more important issues that should be pursued.

Lifeline Inventory. Organizations such as the Federal Emergency Management Agency, Department of Transportation, and American Society of Civil Engineers Technical Council of Lifeline Earthquake Engineering are encouraged to build on the work performed in this project, develop standards for complete lifeline inventories, and coordinate the acquisition of the needed additional and updated data from various lifeline owners.

Lifeline Component Vulnerability. We recommend a major effort to acquire data on lifeline seismic performance and damage, and conduct analysis towards the development of improved component vulnerability functions. This effort should also investigate lifeline recovery data, and incorporate the extensive experience realized during the 17 October 1989 Loma Prieta, California, earthquake, as well as from other damaging earthquakes.

Seismic Hazard Data. We suggest that the U. S. Geological Survey develop, or coordinate through the various states' Office of Geologists, a series of digitized soils/geologic databases.

Economic Analysis and Impacts Data and Methodology. We recommend further research, especially in economic areas such as:

- Economic impacts associated with lifeline disruption,
- Second-order economic effects (e.g., interaction between lifelines),
- Elasticities of demand, or substitution of a lesser disrupted lifeline for a more disrupted lifeline ,
- Inter-regional impacts, and
- So-called "benefits," such as increased economic activity associated with repair, or replacement of older equipment with new technology.

Lastly, we note that this study did not address environmental consequences associated with lifeline disruption, especially the potential for oil spills from broken pipelines in the nation's waterways following a New Madrid event. Investigation of this issue is critically important.