EARTHQUAKE VULNERABILITY OF TRANSPORTATION SYSTEMS IN THE CENTRAL UNITED STATES

Compiled by the Central U.S. Earthquake Consortium
with technical support from MS Technology

September 1996
Revised—August 11, 2000

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PREFACE

Transportation systems in the Central U.S. – including highways, bridges, railways, waterways, ports, and airports – are vulnerable to the effects of a damaging earthquake in the New Madrid seismic zone. Furthermore, damages to transportation systems may extend to several states, which presents transportation officials in government and the private sector with unique problems and challenges.

In an effort to increase awareness of the earthquake risk in the Central U.S., and specifically the vulnerability of transportation systems, The U.S. Department of Transportation collaborated with the Central U.S. Earthquake Consortium to prepare this monograph.

The Central U.S. Earthquake Consortium (CUSEC) is a nonprofit organization, funded by the Federal Emergency Management Agency, that is dedicated to reducing deaths, injuries, damage to property and economic losses resulting from earthquakes occurring in the Central United States. Its members are the seven states that are most vulnerable to earthquakes in this region: Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri, and Tennessee.

Emergency transportation planning is an important element in CUSEC's long-term plan to reduce the earthquake risk in the Central U.S. In this regard, the Consortium has worked closely with the U.S. Department of Transportation on several projects and training activities that address the vulnerability of transportation systems to a New Madrid earthquake, and measures that can be taken to advance mitigation, response and recovery planning. This monograph is a contribution towards this basic effort.

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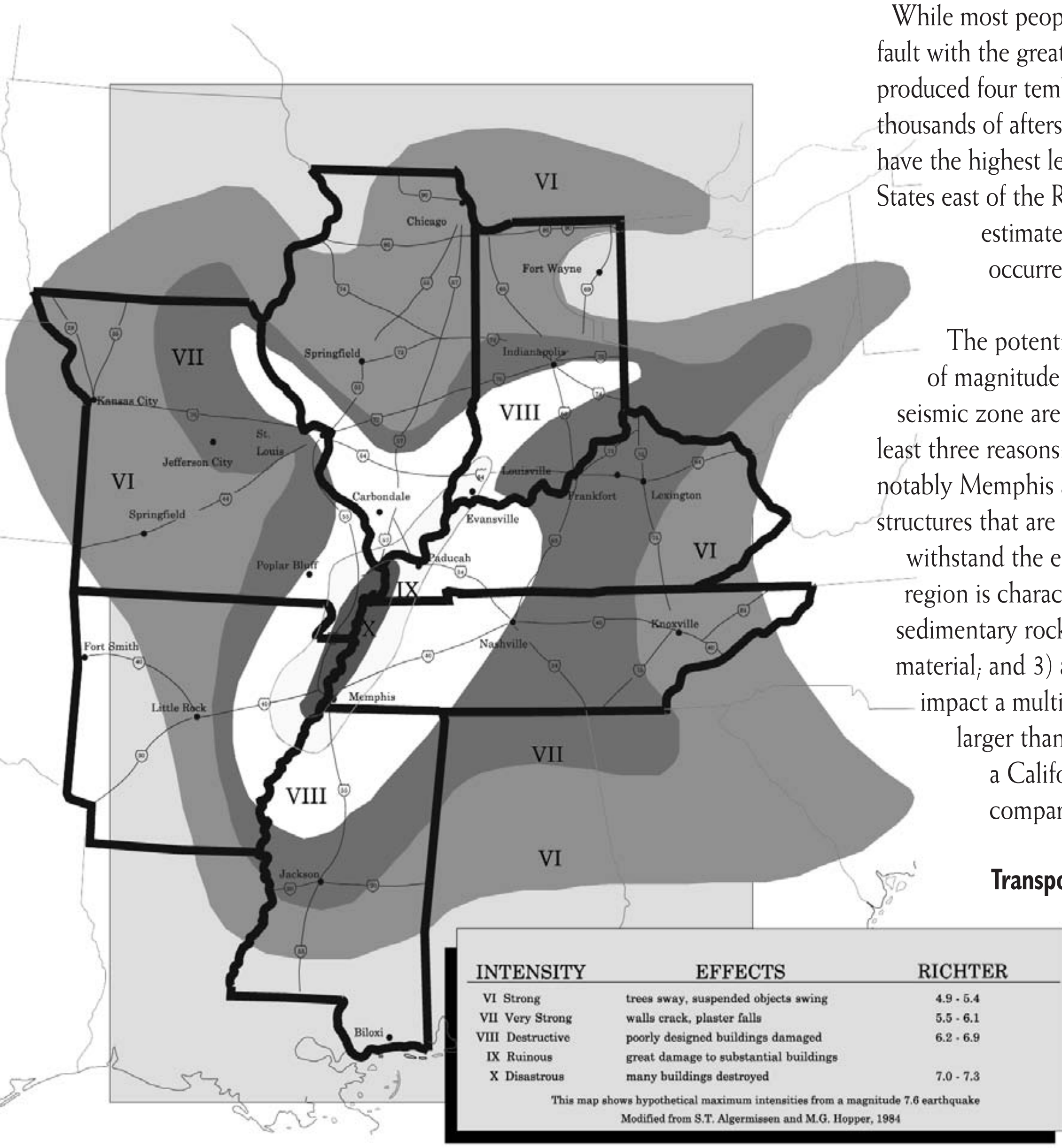
INTRODUCTION

The Central United States is vulnerable to a damaging earthquake. With little or no warning, an earthquake in the New Madrid seismic zone could strike seven or more states, causing major physical, social, and economic disruption to a region that is home to forty million people.

While most people associate the New Madrid fault with the great earthquakes of 1811-12 – which produced four temblors near magnitude 8 and thousands of aftershocks – this region continues to have the highest level of seismicity in the United States east of the Rocky Mountains. Earthquakes of estimated magnitude 6.4 and 6.8 occurred in 1843 and 1895 respectively.



The potential losses from future earthquakes of magnitude 6 or greater in the New Madrid seismic zone are expected to be significant, for at least three reasons: 1) the population centers, notably Memphis and St. Louis, have thousands of structures that are not designed and constructed to withstand the effects of earthquakes; 2) the region is characterized by poorly consolidated sedimentary rocks, which are poor foundation material; and 3) a New Madrid quake would impact a multi-state region (about 10 times larger than the area impacted by a California earthquake of comparable size).

Transportation System Vulnerability

The Central U.S. is a major transportation corridor. Indeed, Memphis – the home of Federal Express – bills itself as "America's Distribution Center."

During the twentieth century, the U.S. has witnessed an explosion in the growth of transportation systems, population, and wealth. In 1900, our nation's transportation system was comprised of three elements: unpaved highway, railroad, and waterway, which accounted for 78 percent of all commodity transport.

Nearly a century later, 90 percent of all travel – measured in passenger miles – is by the highway system. Air travel during this period increased dramatically, accounting for 9 percent of passenger miles. The remaining 1 percent is by rail, water, and local transit.

Our nation's economy, then, is inextricably tied to our transportation infrastructure. To put this into perspective, in 1992, the U.S. Gross Domestic Product was over $6 trillion, of which $728 billion, or 12.1%, was attributable to transportation demand. In addition, over 11 million employees support today's transportation systems.

In essence, the Central U.S. is a major transportation corridor whose infrastructure – roads, bridges, runways, port facilities, rail lines, tunnels – rests atop a landscape that is vulnerable to the effects of earthquakes, including ground shaking and liquefaction (quicksand effect resulting from soil failure).

The consequences from a major New Madrid earthquake would be substantial, estimated from $60 to $100 billion. The destruction to the transportation system would make up a significant portion of those losses.

Generally speaking, the consequences of failure in a transportation system due to an earthquake or other natural disaster can involve:

- Direct loss of life due to collapse or structural failure of the lifeline.
- Indirect loss of life due to an inability to respond to secondary catastrophes, such as fires, and/or provide emergency medical aid.
- Delayed recovery operations.
- Release of hazardous products (e.g., losses from tank cars derailed by track failure, gas leaks from ruptured utility lines) and environmental impacts.
- Direct loss of property and utility service (e.g., the collapse of a bridge carrying utilities).
- Losses due to interruption of access (e.g., export losses due to port damage).
- Disruption of economic activity across the region and nation as well as in the community directly affected.

This monograph is organized into three sections. The first part examines the unique nature of the earthquake risk in the Central U.S. The second section discusses the effects of earthquakes on each component of our nation's transportation system, and how this will affect response and recovery efforts.

The final section of the monograph looks ahead to the challenges and opportunities for transportation officials, emergency managers and others in developing a comprehensive approach to reducing the vulnerability of our transportation system to earthquakes in the Central U.S.

History

Date	Magnitude
1838/06/09	5.1
1843/01/04	6.4
1857/10/08	5.1
1865/08/17	5.2
1891/09/27	5.5
1895/10/31	6.8
1899/04/29	4.3
1903/11/04	5.0
1905/08/21	4.9
1909/05/26	5.2
1909/07/19	4.3
1909/09/27	4.7
1917/04/09	4.9
1922/11/27	4.4

THE EARTHQUAKE RISK

The potential for a destructive earthquake is a real threat to the Central United States.

In the winter of 1811-12, the central Mississippi Valley was struck by three of the most powerful earthquakes in the U.S. history. On December 16, 1811, the residents of the town of New Madrid, Missouri were abruptly awakened by violent shaking from the first of three magnitude 8 earthquakes in the region. Thousands of aftershocks were to rock the region during that winter.

The earthquakes of that memorable winter were not freak events. On the contrary, scientists have learned that strong earthquakes in the central Mississippi Valley have occurred repeatedly in the geologic past. The area of major earthquake activity also has frequent minor shocks and is known as the New Madrid seismic zone.

of Damaging Earthquakes in the Central U.S.

Location	Date	Magnitude	Location
Southern Illinois	1925/04/27	4.9	Indiana-Illinois border
Marked Tree, Arkansas	1927/05/07	4.8	Northeastern Arkansas
Southern Illinois	1931/12/16	4.1	Northern Mississippi
Southern Missouri	1962/02/02	4.2	New Madrid, Missouri
Southern Illinois	1963/03/03	4.7	Southern Missouri
Charleston, Missouri	1965/10/21	4.6	Eastern Missouri
Vincennes, Indiana	1968/11/09	5.4	South-central Illinois
Southeastern Missouri	1969/01/01	4.3	Central Arkansas
Mississippi Valley	1976/03/25	5.0	Eastern Arkansas
Illinois	1982/01/21	4.4	North-central Arkansas
Illinois	1987/06/10	5.0	Southeastern Illinois
Indiana-Illinois border	1990/09/26	4.8	Southeastern Missouri
Eastern Missouri	1991/05/03	4.6	Southeastern Missouri
Illinois	1998/09/25	5.0	Ohio/Pennsylvania border

Multi-State Impact

Earthquakes in the central or eastern United States affect much larger areas than earthquakes of similar magnitude in the western United States. For example, the San Francisco, California earthquake of 1906 (magnitude 7.8) was felt 350 miles away in the middle of Nevada, whereas the New Madrid earthquake of December 1811 (magnitude 8.0) rang church bells in Richmond, Virginia, 1,000 miles away. Differences in geology east and west of the Rocky Mountains contribute to this significant contrast.

Recent Earthquakes in Central U.S.

Moderate earthquakes in the magnitude 5.8 to 6.9 range occur with more frequency in the Central U.S. than larger, potentially catastrophic earthquakes. Furthermore, the loss of life and destruction in recent earthquakes of only moderate magnitude dramatically illustrate the need for earthquake preparedness programs in the Central U.S. (for example, 33 lives and $20 billion in the 1994 Northridge, California earthquake and 5,500 lives and $100 billion in the 1995 magnitude 6.9 Kobe, Japan, earthquake).

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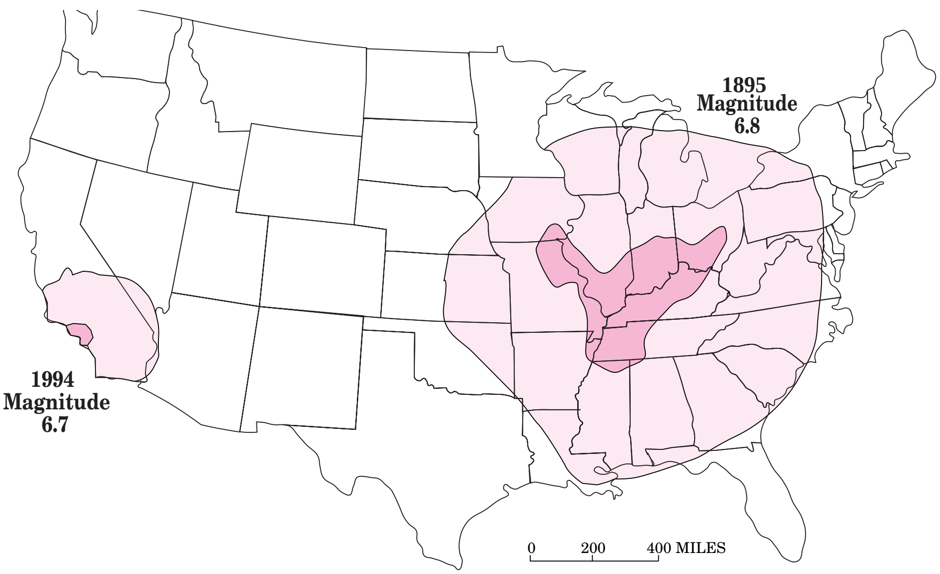
Magnitude		Recurrence time (years)
> 6.0	> 6.3	70 (±15)
> 6.6	> 7.6	254 (±60)
> 7.0	> 8.3	550 (± 125)

Source: Center for Earthquake Research and Information
University of Memphis



Shaking felt, but little damage to objects

Minor to major damage to buildings and their contents

Reference: Schweig, Eugene et al., U.S. Geological Survey Fact Sheet-168-95 1995

The multi-state impact of a New Madrid earthquake is the primary reason that the Central U.S. Earthquake Consortium was established in 1983 to coordinate member state planning efforts.

Earthquakes in the "moderate" range occur on the average of every fifty years in the New Madrid seismic zone. The last earthquake in this magnitude range was a 6.8 quake in 1895, so statistically speaking, the region is due for a moderate, but damaging earthquake.

ROBABILITY ESTIMATES
MADRID SEISMIC ZONE

Probability of recurrence (percent) next 15 years	next 50 years
40-63	86-97
5.4-8.7	19-29
0.3-1.0	2.7-4.0

Probability of Future Damaging Earthquakes

The probability of a moderate earthquake occurring in the New Madrid seismic zone in the near future is high. Scientists estimate that the probability of a magnitude 6 to 7 earthquake occurring in this seismic zone within the next 50 years is higher than 90 percent.

Earthquake Induced Hazards

A central question becomes, how can earthquakes affect transportation systems?

When earthquakes occur, there are a number of ways in which transportation systems can be affected. Typically, one thinks of the ground shaking hazard that causes major damage or failures. However, there are other earthquake related hazards that can affect transportation systems. These hazards are: (1) faulting, which results in rupture of the earth's surface; (2) ground failures, which can result in liquefaction, slope instability, and subsidence; and (3) induced physical damages, such as flooding, dam or levee failures, landslides, fires and hazardous materials releases.

Faulting

An earthquake occurs when a fracture, commonly known as a fault, ruptures due to stresses that have built up in the crust. Fault ruptures are more common in the western U.S.

Tremendous surface displacements did occur during the 1811 and 1812 New Madrid earthquakes, when land rose and fell as much as 10 feet. Several lakes were created during these great earthquakes, including Reelfoot Lake in northwest Tennessee.

Reelfoot Lake

Liquefaction

Liquefaction typically occurs in layers of sandy soil that are located in the upper 30 feet of the soil strata where a high water table exists. This phenomena is caused by ground shaking, which rearranges soil particles in such a fashion that a "quicksand" effect results.

When liquefaction occurs, two conditions can result: (1) loss of bearing strength needed to support the foundations of roads, bridges, and buildings; (2) lateral spreading where a layer of stable soil can slide over the top of a liquefied layer.

Another type of earthquake induced liquefaction soil failure is a sand blow. As the soil particles lose their ability to provide bearing strength, the weight of the soil above causes pressure in the liquefied layer to build up. This can cause sand and water of the liquefied layer to be jettisoned to the surface through weak points in the overlaying soil. Sand blows were extensive in the New Madrid earthquakes of 1811-12, and can still be seen today.

Slope Stability

Slope stability failures, or landslides, occur when unstable slopes lose their cohesive stability during ground shaking. One of the largest rock slides occurred during the 1959 Hebgen, Montana, earthquake, when a complete mountain side was dislodged causing 80 million tons of rock mass and debris to end up at the bottom of the mountain.

Slope stability can be a major problem in hilly areas in the Central U.S., and lead to serious problems with road and railway embankment failure.

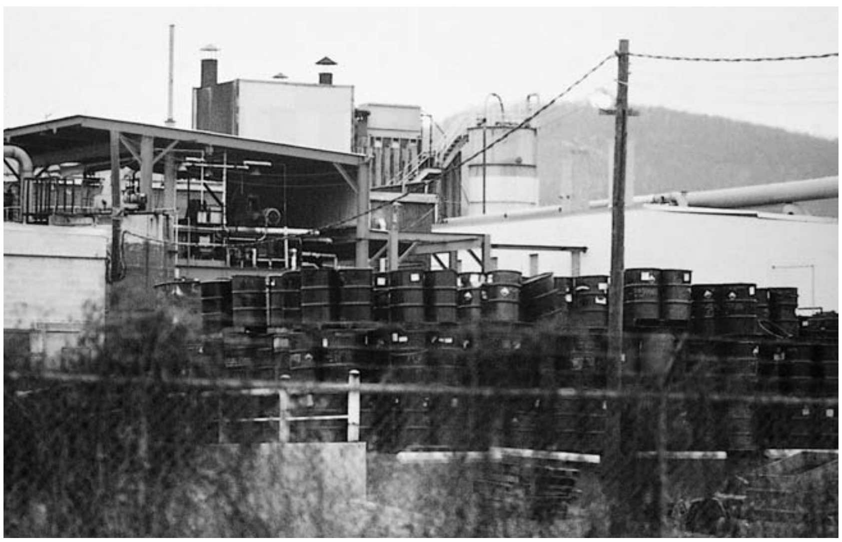
Dam or Levee Failure

The Central U.S. has historically been susceptible to flooding. The 1993 Midwest Floods clearly illustrate the consequences of widespread flooding, and the key role that dams and levees play in flood protection in this part of the country.

Earthen dam failure, Morgan Hill, CA

These same levees and dams are vulnerable to ground shaking. Given the large number of dams and the extensive network of reservoirs and levees along the region's river systems, significant flooding from earthquake induced breaks in dams and levees should be expected at high water periods. Roads and bridges would also be damaged, compounding response and recovery efforts.

Hazardous materials releases and spills are a major earthquake induced hazard, one that will have a regional impact. The transportation system that we depend on to move hazardous materials products is clearly vulnerable to earthquakes, as reflected in the following section.



Hazardous Materials Spills

Hazardous materials are a by-product of the economy of the Central U.S. As a major transportation corridor, tremendous volumes of hazardous materials pass through this region by rail, highway, and river. Oil and natural gas pipelines also crisscross near or through the New Madrid seismic zone, transporting 4 million barrels per day of crude oil, petroleum products and natural gas. As metropolitan areas in the Central U.S. continue to grow, more and more people live and work near industrial and commercial facilities that process or store hazardous materials.

EFFECTS OF EARTHQUAKES ON THE TRANSPORTATION SYSTEM

Recent earthquakes, including the Northridge, California event (1994), show quite dramatically the damages that earthquakes can inflict on roads, bridges, and other components of our nation's transportation system.

Although transportation system disruption or failure is not considered a major risk to life safety, the socioeconomic consequences can be particularly devastating to the general public. These include the primary impacts that flow directly from impeded access to hospitals, evacuation areas, emergency relief centers, and fire departments, and the secondary impacts due to closed mass-transit facilities and the inability to get to or from work for an extended period of time.

A recurring theme of this monograph is that our nation's transportation network should be viewed as an interdependent system of components (e.g., roads, bridges, tracks, retaining walls, tunnels, embankments, etc.), and the failure of any one component can cause problems or even failure in other parts of the system.

The following section examines in more detail the effects of earthquakes on key components of the transportation system, with implications for pre-disaster mitigation (steps that can be taken to minimize damages), and response and recovery planning.

Highway Transportation

The major components of the highway transportation system are pavements, bridges, overpasses, viaducts or elevated expressways, tunnels, embankments, slopes, avalanche and rock shelters, retaining walls, and maintenance facilities. Roadways and bridges are of primary concern, since their loss of function will have the greatest impact on the ability to move people and equipment after the earthquake.

Roadways will sustain damages in a New Madrid earthquake, primarily from surface displacements, liquefaction, slope instability and earthquake induced flooding from broken levees during high water events.

Pavements will crack in a damaging New Madrid earthquake, principally due to ground failure (such as liquefaction). Critical links in the interstate system, including Interstate 55 and Interstate 40, would in all likelihood be closed due to failures to approaches to bridges, and damage to the pavement itself.

Bridges and overpasses are the most vulnerable component of the transportation system, as evidenced in recent earthquakes in California and elsewhere. In 1964, nearly every bridge along the partially completed Cooper River Highway in Alaska was seriously

Collapsed Interstate 880, Loma Prieta 1989 damaged or destroyed. Seven years later, the San Fernando earthquake damaged more than 60 bridges on the Golden State Freeway in California. It is estimated that it cost the state approximately $100 million to repair and replace these bridges, including the indirect costs due to bridge closures. In 1989, the Loma Prieta earthquake damaged more than 80 bridges and overpasses, and in the Northridge earthquake (1994), 163 bridges and overpasses were damaged, six of which collapsed. Bridges and overpasses in a New Madrid earthquake would sustain major damages. *A Scenario for a 7.6 Earthquake in Charleston, Missouri*, prepared by the Federal Emergency Management Agency (FEMA), determined that approximately 1500 bridges in a five state region would be nonfunctional immediately after a 7.6 earthquake, with an estimated 500 of these bridges remaining nonfunctional one month after the event.

Memphis and St. Louis will face major problems of their own. A FEMA loss estimation study *(An Assessment of Damage and Casualties for Six Cities in the Central U.S. Resulting from Earthquakes in the New Madrid Seismic Zone, 1985)*, determined that in a 7.6 earthquake, almost all bridges and overpasses in the city of Memphis and Shelby County would experience "major to destructive" damage. A companion study *(Estimated Future Earthquake Losses for St. Louis City and County, 1990)* of a magnitude 7.6 earthquake concluded that St. Louis City and County would lose serviceability to 50 percent of the long span bridges. Other bridges would experience 26 to 88 percent loss of serviceability.

Collapsed Bridge, 1964 Japan Earthquake

The vulnerability of bridges and overpasses in the Central U.S. to a damaging earthquake has major implications for post-disaster response, and long term recovery efforts. Access to disaster sites is critical to effective response operations. The failure of bridges and overpasses will seriously impede response efforts, both interstate and intrastate.

Thousands of bridges will need to be inspected before they can be used, which means that priority must be given to the formation and coordination of State and federal bridge inspection teams. The repair of bridges will have a direct impact on the pace of long-term economic recovery, which will be a function in large part of the ability to move goods and services across the region. Finally, the large area of damages will complicate the ability of workers, goods, and equipment to move into or within the region after the earthquake.

Railroad Transportation

While the growth of the railroad system peaked in this country at the turn of the century, our nation still depends on rail to move people and goods.

Although the number of miles of rail has been reduced by 50 percent since 1900, the tons and ton-miles of freight being transported by rail has increased. Passenger service is increasing. Today, Amtrak passenger service carries 20 million passengers a year over 24,000 miles of track to 530 locations.

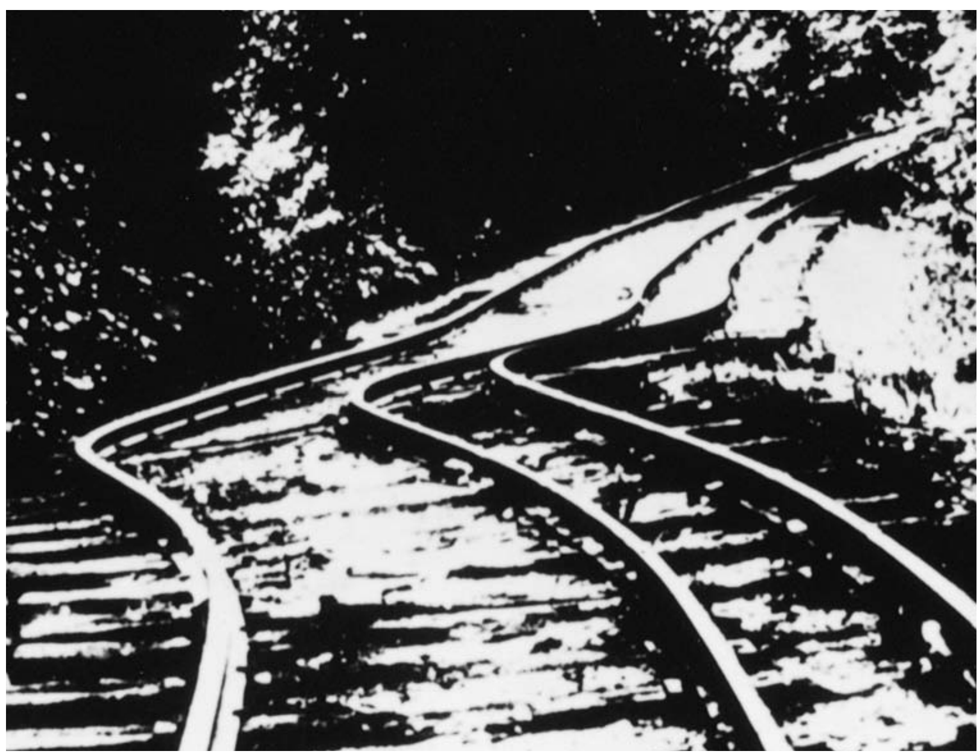
The railroad system is vulnerable to earthquakes in much the same way as the roadway system is. A survey of damage to railroad components during past earthquakes in the United States and Japan shows damage to bridges, embankment failures, vertical and horizontal track misalignments, tunnel misalignments, failure of tunnel linings, structural damage to railroad buildings, and overturned rail cars and locomotives.

The weak link in the railroad system in the Central U.S. is bridges. Most of the railroad bridges in the seven state New Madrid region were built prior to 1920, and did not include earthquake loads. Railway bridges will have to be inspected and repaired, which will compound recovery efforts.

A potentially significant problem in the Central U.S. following an earthquake is hazardous materials releases and spills from overturned tank cars. Accidents can result from a number of scenarios: failed bridges, misaligned tracks, embankment failure, tunnel collapse, and traffic signal failure.

Railroads can play an important role in the recovery process following a damaging earthquake in the Central U.S. Heavy equipment will need to be moved into the damaged region to support a range of tasks associated with the rebuilding process. This needs to be factored into the transportation planning process.

In the final analysis, it is important to recognize that our nation's rail system is privately owned. Efforts to reduce the vulnerability of the rail systems to natural disasters is primarily a private sector responsibility.



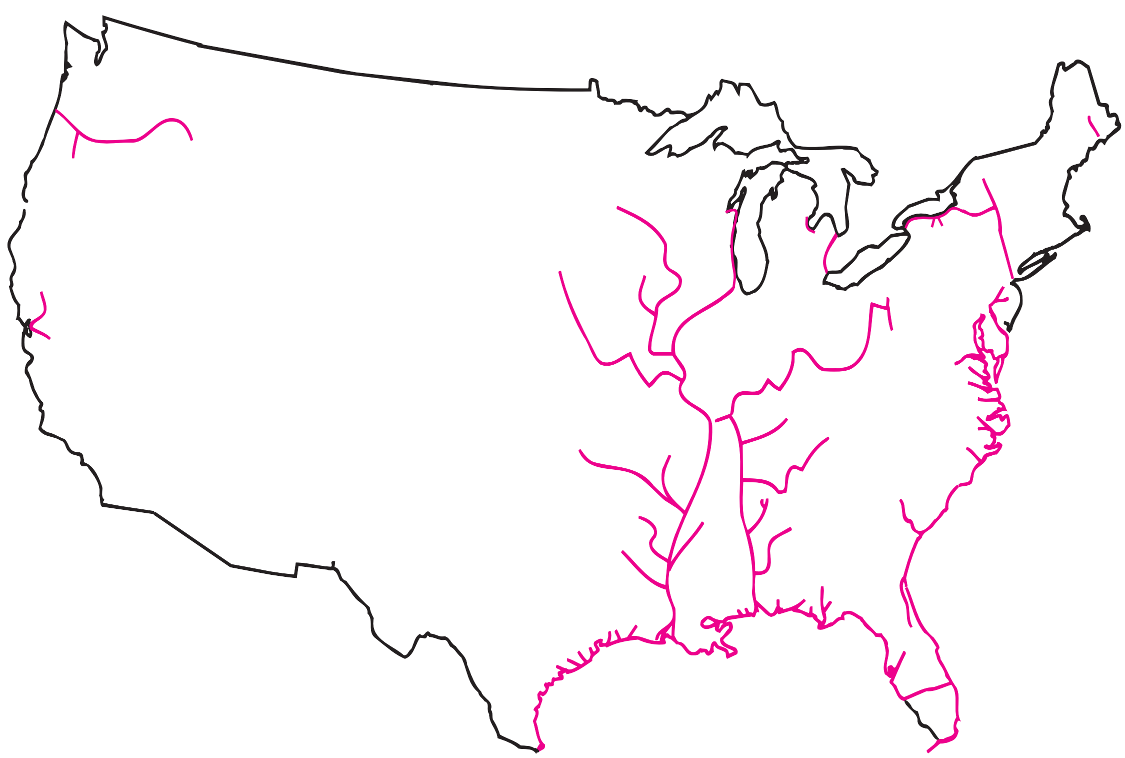
Bent Railroad tracks, Charleston 1886

Waterway Transportation

The New Madrid region plays a pivotal role in the United State's water-borne transportation system. The Ohio, Missouri, and Mississippi Rivers are used extensively by barges to transport a wide variety of manufactured goods and petroleum. The many ports along these rivers (including the highly-trafficked ports at Memphis and St. Louis) and an extensive series of locks, dams, and reservoirs are highly exposed to earthquake induced ground shaking and liquefaction.

Again, waterway transportation is a system of interlocking components. To better understand the potential impact of an earthquake on this system, it is important to view the waterway system in the Central and Eastern U.S. Generally speaking, water-borne commodities traffic within the Central and Eastern U.S. occurs over three types of navigational waterways: 1) coastwise, which is traffic along the coasts and traffic receiving a carriage from deep sea; 2) lakewise, which is traffic within the Great Lakes; and 3) internal, which takes place solely on inland waterways.

As reflected in the map of the inland waterway system below, the Mississippi River and its tributaries, and the Gulf Intracoastal Waterway and the rivers that intersect it, are an interconnected network that accounts for 86 percent of the route length of the U.S. water traffic system. In 1993, over 2.0 billion tons of foreign and domestic commodities were shipped using water-borne traffic.



Vulnerability of Inland Waterways and Ports

An earthquake in the New Madrid seismic zone would have two direct impacts on the inland waterways system: first, it could seriously impede the navigability of the rivers and canals; and secondly, an earthquake could cause serious damages to port facilities.

The 1993 Midwest Floods demonstrated once again how important this water-borne transportation system is to our nation's economy. For 52 days, it was impossible to traverse the Missouri, Illinois, and upper Mississippi rivers. A total of 26 of the 30 locks on the Mississippi were closed. It was estimated that 5,000 barges were affected, and the costs of delays in commodity traffic was in the millions of dollars per day.

A New Madrid earthquake would cause considerably more damage, to a wider area, leading to longer delays. The reason is that the major components of inland waterways – channels, banks, levees, and locks and dams – are vulnerable to ground shaking and liquefaction, which could lead to their failure. This in turn would have a significant impact on navigability. Landslides and bank failures could block channels. Debris from fallen trees and other materials could hinder navigation. Uplift and subsidence, could result in changes in channel depth or the course of the river. Liquefaction could result in large lateral flows that could block channels. Channels can also be blocked by the collapse of bridges.

The five inland waterways at highest risk are the Missouri, Mississippi, Ohio, Tennessee, and Illinois Rivers. This is due to at least three factors. First, sections of these river systems are within areas that can produce strong ground shaking and liquefaction; second, these are rivers that are used to transport large volumes of commodities; and finally, these are rivers that, if unnavigable, can have direct and prolonged consequences for the national economy.

In essence, inland waterways, which are counted on to provide an economical source of transportation for the movement of bulk goods across the region, can suddenly become dysfunctional as a result of an earthquake. Furthermore, alternative modes of transportation for bulk goods – notably railroad – would also be rendered inoperable for extended periods of time.

Ports

The damage sustained to the Port of Kobe in the 1994 earthquake drew the world's attention to the key role of ports in national and international trade and commerce, and the vulnerability of these facilities to earthquakes. Within seconds, the Port of Kobe, one of the largest container facilities in the world, sustained major damage, primarily due to massive liquefaction (ground failure).

The port facilities in St. Louis and Memphis, and to a lesser extent New Orleans, are highly susceptible to the effects of earthquakes.

To reduce the vulnerability of ports to earthquakes is a complex undertaking. The reason is that ports are a multitude of different components that can be grouped under three main categories: 1) Geotechnical and retaining structures – which include fill areas, retaining structures/dikes, and berthing structures; 2) Cargo handling and storage components – which consist of container storage areas, liquid storage tanks, and material handling equipment such as cranes, conveyors, transfer towers, and stacker equipment; and 3) Infrastructure components, which can include utilities (for providing power, communication, water, sewage control and transport, etc.), pipelines, buildings, railroads, and elevated viaducts and bridges.

The bottom line is the port facilities in the Midwest are going to experience damages – potentially severe damages – depending on the magnitude, location, and duration of the earthquake, and the presence of aftershocks. This will have direct implications for response and recovery efforts.

Emergency responders need to be concerned with potential environmental risks associated with possible spills of hazardous and toxic materials. Fire following earthquakes is another real problem at port facilities, based on recent experience. More emphasis needs to be given to the development of emergency preparedness plans for managing a coordinated response to emergencies at port facilities.

Pre-disaster recovery planning for a New Madrid earthquake also must take into consideration the consequences of loss of function of port facilities, and the associated economic impacts.

Port of Kobe

In the final analysis, greater attention needs to be given to the systematic incorporation of seismic design and planning of port facilities and their components. The objective is to improve – over time – the seismic performance of key parts of port facilities, so that when the earthquake occurs, restoration times are reduced, lives are protected, and environmental problems are reduced.

Air Transportation

Air transportation is the fastest growing mode of transportation in the U.S., and is becoming increasingly important as the economy becomes more global. Air transportation has also become a central part of the local economies of both Memphis – home of Federal Express and the nation's busiest cargo airport – and St. Louis, home of McDonnell Douglas and the main hub of Trans World Airways.

Airports, like all other transportation facilities, will suffer damage in an earthquake. Of particular concern are six components of airport facilities that are most vulnerable: terminals; runways; power, communication, and radar; and liquid fuel and transport. The functionality of an airport will depend, to a large extent, on what happens to these key components.

A study (ATC 25, 1991) of the impact of a magnitude 8.0 New Madrid earthquake on 1678 airports in Illinois, Missouri, Arkansas, Tennessee, Kentucky, and Mississippi determined that 474 experienced light to destructive damage, with 60 of these experiencing heavy to destructive damage.

Airport terminals have typically been designed and constructed to comply with local building codes. It was not until 1990 that federal owned or funded buildings – including airport facilities – had to be designed for earthquakes. However, even if an airport is designed and constructed to conform with building codes which require seismic design, that design represents only minimum standards to provide for life safety. This translates into the following conclusion: terminals and control towers will suffer damage during an earthquake.

The performance of control towers and sensitive equipment are particularly important in the immediate aftermath of an earthquake. Backup power and continuous operating communication and radar systems are vital to airport operations and to the planes in the air. One FEMA seismic study determined that between 15 and 20 percent of the 300 airports in the five state region in the Central U.S. would be nonfunctional following a 7.6 earthquake. Damages to control towers accounts for much of the loss of function.

Because airports require large flat areas to accommodate the landing of aircraft, many cities have located airports near rivers, or large bodies of water. The runways at these airports may be located on fill land, or soil that is otherwise highly vulnerable to liquefaction. However, except where major liquefaction occurs, runways can be repaired quickly.

Liquid Fuel and Transport

Airplanes need fuel, and this fuel is typically stored in above ground storage tanks and is transported through underground pipelines to airplane gate areas. The immediate problem is the threat of fire and explosion as a result of rupture to the tanks and underground pipelines. For the most part, building codes do not address the seismic design of liquid fuel storage tanks or underground pipelines. Experience from previous earthquakes indicate that liquid storage tanks often fail at the transfer connections between the piping and the tank. Tank rupture can also occur from the combined effects of structural failure and fuel sloshing. These problems can be addressed in a broad based mitigation effort for transportation facilities, discussed in the final sectionof this monograph.

A central question, then, is what is the cumulative impact of a damaging earthquake on airports in the Central U.S., and what are the implications for response and recovery?

A major earthquake in the New Madrid seismic zone will undoubtedly cause significant damages to airport facilities – terminals, runways, control towers, liquid fuel tanks and pipelines – in those communities near the epicenter of the earthquake. These airports and heliports may not be operational for weeks following the earthquake, which means that they will not be available for incoming and outgoing flights in the immediate response phase of the disaster operation.

From a regional perspective, however, there are a sufficient number of airports that will not be damaged to compensate for those that are. A 1991 study (*Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States, ATC-25*) concluded that in a magnitude 8 earthquake, the impacted states still maintained approximately 80 percent of their airport runway capacity and 20 percent on terminals. The study noted that the functionality of key national and regional hubs (e.g., Memphis and St. Louis) is the critical issue.

To this point, the monograph has focused on the nature of the earthquake hazard in the Central U.S. and the potential effects of earthquakes on key components of our nation's transportation system – bridges and highways, railways, ports and harbors, and airport facilities.

The final section examines some of the challenges and opportunities in developing and implementing a comprehensive program to address the vulnerability of transportation systems in the Central U.S.

REDUCING THE VULNERABILITY OF TRANSPORTATION SYSTEMS: CHALLENGES AND OPPORTUNITIES

A broadly based initiative to reduce the vulnerability of the transportation system in the Central U.S. to earthquakes and other hazards is a complex undertaking that will involve the input and expertise of federal, state, and local governments, the private sector, and the research community.

This section sets forth a framework for future action, organized under four headings: 1) Vulnerability Assessment; 2) Awareness and Education; 3) Mitigation; and 4) Response and Recovery.

Vulnerability Assessment

The starting point for a long-term transportation vulnerability reduction initiative is a scientifically based assessment of the vulnerability of key components of transportation systems.

In September, 1988, the Applied Technology Council (ATC), with support from FEMA, initiated an assessment of the seismic vulnerability of lifeline systems (electric power, gas and liquid fuels, telecommunications, transportation, and water supply and sewers) nationwide. The purpose of the project was to develop a better understanding of the impact of lifeline disruption caused by earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies.

Four basic steps were followed to estimate lifeline damage and subsequent economic disruption for given earthquake scenarios: development of a national lifeline inventory database; development of seismic vulnerability functions for each lifeline system or system component; characterization and quantification of the seismic hazard nationwide; and development of estimates of direct damage and of indirect economic loss for each scenario earthquake.

CUSEC State Transportation Task Force

On June 28th 2000, the seven CUSEC State DOT's formed what is now known as the CUSEC State Transportation Task Force. The Transportation Task Force will provide a formal, coordinated, regional approach to deal with earthquake related transportation issues in the Central U.S. The Task Force will collaborate with other organizations on common issues, and become an integral part of the Central United States Partnership, contributing to the development of a coordinated long-term strategic plan to address earthquake issues in the Central U.S.

Assessing vulnerability of transportation systems and other lifeline components is complicated by several factors: lack of available data, technical difficulties, and the interdependence of the lifelines. For example, transportation systems are severely affected by the loss of power, particularly in urban centers where mass transit and traffic signals depend on electric power.

Vulnerability assessment, then, is fundamental to our understanding of the potential impacts of earthquakes and other hazards on our buildings, infrastructure, and people. The federal government will continue to take the lead role in vulnerability assessments, and the use of this information to establish guidelines and standards for design and construction of transportation systems, and other lifeline components.

Awareness and Education

Information on the vulnerability of transportation systems to earthquakes and other hazards can be used in an awareness and education campaign that raises the level of understanding of natural hazards, their effects, and steps that can be taken to reduce hazard vulnerability.

Awareness and education efforts can target a broad range of groups: transportation officials (federal, state, local), other government officials, elected and appointed officials, the media, emergency managers, researchers, the design and construction professions, the private sector, educators, and the public. These programs should capitalize on existing research and lessons learned from recent disasters. Finally, there is a growing market of software programs, including interactive software, that can be effectively used in a program to increase awareness and education of the vulnerability of transportation systems to earthquakes and other hazards.

Mitigation

Mitigation – those actions that can be taken prior to a disaster to minimize damages and losses – is at the heart of a long-term commitment to reducing the vulnerability of transportation systems to all natural hazards.

The cornerstone of a transportation lifeline mitigation program is the development of design criteria and standards that will guide and facilitate transportation mitigation efforts, and provide consistent minimum recommended levels of facility engineering design and construction practice.

To date, very few standards have been written explicitly for the design and construction of transportation systems. Those that do exist are only for components (e.g., bridges), and none addresses system performance.

The best example of transportation standards is the seismic specifications for new highway bridges, adopted by the American Association of State Highway and Transportation Officials in 1990. These AASHTO requirements are philosophically defensible and nationally applicable. On the other hand, standards for upgrading existing highway bridges are not as well developed.

A plan to reduce the vulnerability of transportation systems in the Central U.S. will necessarily require a comprehensive, collaborative approach, led by the Federal government. Public Law 101-614, the National Earthquake Hazards Reduction Program (NEHRP) Reauthorization Act directs FEMA, in consultation with the National Institute of Standards and Technology (NIST), to develop a "plan, including precise timetables and budget estimates, for developing and adopting, in consultation with appropriate private sector organizations, design and construction standards for lifelines," including transportation systems.

Demonstration projects are a key element in the recommended approach to carrying out the Congressional mandate. In essence, these projects provide opportunities to show early successes of the program. They should be encouraged in various seismic zones for the retrofit and or design of highway and railway structures. This is particularly useful for the implementation of new and innovative technologies, such as base isolation and protective systems for bridges.

Kentucky's Bridge Retrofit Program

The State of Kentucky has embarked on an aggressive program to retrofit seventy-seven seismically vulnerable bridges along priority routes in Western Kentucky.

The retrofit program began as a result of a study by the Kentucky Transportation Research Program, entitled "Earthquake Hazard Mitigation of Transportation Facilities," completed in January, 1988. That study examined the vulnerabilities of emergency access routes to each of the twenty-six western most counties of Kentucky. It recommended a list of bridges along critical access routes for retrofitting. The total estimated cost to complete the retrofit is $1 million, eighty percent of which will be federal funds.

Generally, the retrofit consists of the use of steel cables running through bridge piers and tying the spans together. The improvements cannot guarantee a bridge will not fail during an earthquake, but it should help to prevent the loss of spans which might otherwise shake off the piers. In any event, the retrofit program will improve the functionality of the bridges after an earthquake, and thus improve the overall response and recovery operation. Other CUSEC states are implementing similar bridge retrofitting programs under the AASHTO guidelines.

Response and Recovery

A New Madrid earthquake will place unprecedented demands on federal, state and local transportation officials and emergency managers. There will be no warning. Multiple states will be impacted. Communications will be lost. Decisions will be made in the absence of situation assessment information. States will request critically needed transportation resources in the first days and weeks following the earthquake; criteria for "resource adjudication" will need to be established.

In short, there is a compelling need for pre-disaster policies, plans and procedures to guide Transportation (Emergency Support Function #1) decisions in the first 72 hours following an earthquake, the first thirty days, and beyond.

Because of the large area that would be impacted – up to ten states in four Federal regions – there needs to be an over-arching "umbrella" plan that addresses Transportation priorities and coordination issues for a New Madrid earthquake. Such a plan can:
1) incorporate the loss estimation data that reflects direct loss estimates and functionality losses; and 2) serve as a central, unifying plan to ensure a coordinated approach to transportation response and recovery.

A New Madrid Transportation Plan and Strategy, which would be the product of an intergovernmental-private sector planning process, can address the following:

1. Loss estimates and functionality assessments for select earthquake scenarios.
2. Common set of planning assumptions for Federal, State, and local governments.
3. Criteria for decisions on establishing field operations in a multi-state, multiple Federal region disaster.
4. How to prioritize the allocation of resources to multiple impacted areas.
5. State versus Federal roles in determining priorities and planning for infrastructure repair.
6. Procedures and criteria for conflict resolution in meeting requests for resources.
7. Pre-disaster determination of conditions that must be present before federal transportation support is withdrawn.

In essence, a New Madrid earthquake will impact the strategic center of the national transportation hub, and affect the movement of goods and services in a manner that will have profound implications for our national economy. In this context, it is important to develop and test an intergovernmental plan and strategy that addresses transportation issues.

USEFUL PUBLICATIONS

An Assessment of Damage and Casualties for Six Cities in the Central United States Resulting From Earthquakes in the New Madrid Seismic Zone. *Central United States Earthquake Preparedness Project October 1985, Federal Emergency Management Agency.*

This report was the first loss estimation study conducted for a damaging earthquake in the central United States. It was based on the occurrence of magnitudes 7.5 and 8.5 New Madrid earthquakes. The report included estimates of the losses to transportation systems. *Available from Federal Emergency Management Agency, Washington, D.C.*

Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States (ATC-25). *Earthquake Hazard Reduction Series 58, Federal Emergency Management Agency, 1991, FEMA 224.*

This study inventoried the transportation systems of highways, bridges, railroads, airports, and ports; energy systems of electric power, gas and liquid fuel transmission; emergency service facilities in broadcasting and hospitals; and water aqueducts and supply. It considered the occurrence of magnitudes 7.0 and 8.0 New Madrid earthquakes. *Available from Federal Emergency Management Agency, Washington, D.C.*

Mitigation of Damage to the Built Environment. *Central United States Earthquake Consortium,* 1993. This is one of five monographs prepared for the 1993 National Earthquake Conference that focused on earthquake mitigation in the central and eastern United States. Part II of the monograph consists of six chapters that focus on lifelines with Chapter 7 discussing highways and railroads, Chapter 8 discussing ports and air transportation systems, and Chapter 12 discussing standards for lifelines. *Available from Central United States Earthquake Consortium, Memphis, Tennessee.*

American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering. *Fourth U.S. Conference on Earthquake Engineering–Lifelines Earthquake Engineering.* A set of proceedings on earthquake vulnerability, mitigation, and preparedness of life lines that includes a number of state-of-the-art papers on various elements of transportation systems. The American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering has a series of other pertinent publications. Available from the *American Society of Civil Engineers, New York.*

Seismic Damage to Railroad Bridges in the United States. *Paper prepared by J.M. Pauschke, and published in the Proceedings of the Fourth U.S. National Conference on Earthquake Engineering, Volume 1, Earthquake Engineering Research Institute, 1990.*

This paper provides a summary of earthquake damage to railroad bridges and discusses why railroad bridges appear to perform better than highway bridges.

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