The Potential Impact of a Mid-America Earthquake on the Railroad Network

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ABSTRACT

The Mid-America earthquake region encompasses an important segment of the US rail network. Using geographical information systems (GIS) software, we estimated that approximately 2,107 rail route miles and 2,082 bridges are in areas with a 2% probability of experiencing ground motion sufficient to cause moderate to severe damage in the next 50 years. Among the bridges at risk, eight cross the Ohio or Mississippi Rivers. We developed a simple cost-analysis model to evaluate options for retrofitting railway bridges for enhanced seismic resistance. Limitations in the data prevent firm conclusions, but the results indicated that it was probably not cost-effective to retrofit most short to medium-sized bridges in the region, but there were plausible scenarios in which retrofit of the major bridges could be rational.

INTRODUCTION

In the winter of 1811-12, over 2,000 earthquakes occurred in a region near the confluence of the Mississippi and Ohio rivers near New Madrid, Missouri. Although precise seismic measurement techniques were not available at that time, evidence indicates that between six and nine of the earthquakes registered a moment magnitude of 7.0 or greater (*1*) and were felt as far away as Mexico, Canada, and Washington D.C. (*2*). The largest earthquake registered a moment magnitude of over 8.5 and caused the Mississippi River to flow backwards creating numerous waterfalls and widespread soil liquefaction throughout the area.

Historical and geological data shows that these New Madrid area earthquakes were not isolated events. Strong earthquakes have occurred repeatedly and the region continues to have the greatest level of seismicity in the United States (U.S.) east of the Rocky Mountains (*2*). Over 4,600 low magnitude earthquakes have been recorded in the Mid-America region since 1974 (*3*).

When the next major Mid-America earthquake occurs, the potential losses in the region are expected to be substantial (*4*) because:

- many of the structures in the region were not designed to be seismically resistant
- there is poor soil foundation material in the area
- the size of the potentially affected area is large

The probability of a severe Mid-America earthquake in the next 50 years is not remote. There is a 2% chance of an earthquake causing peak ground accelerations (PGA) (measured as a percentage of gravity or g) in excess of 20% g over 43,367 square miles of the region, and PGA values exceeding 40% g over an area of 9,647 square miles (Figure 1). Railroad bridge engineers believe that PGA values greater than 20% g are capable of damaging railroad bridges. These factors, along with knowledge gained from past earthquakes, indicate that the railroad network in the Mid-America region is vulnerable to damage in a major earthquake.

Importance of the Rail Network in the Mid-America Region

A major component of the national transportation system is the railroad network. In 1999, there were approximately 2,107 route miles of active trackage in the Mid-America region exposed to potentially damaging peak ground accelerations (Figure 2A). This represents 2.2% of the total route miles in the U.S. Furthermore, many high-density rail lines traverse the Mid-America region, including several with annual traffic levels greater than 60 MGT (Figure 2B). The total gross ton-mileage in 1999 for rail lines in the region was 96.2 billion, which represented 3.2% of the U.S. total.

The Mid-America region is of particular significance to the nation s rail network. The Mississippi and Ohio Rivers both traverse the region. Much of the nation s rail traffic traveling through the central U.S. must cross one or both of these rivers. Eight major bridges, five over the Mississippi and three over the Ohio, carry approximately 245 million tons of freight per year (*5*), accounting for 11.4% of the annual rail freight tonnage originated in the U.S. The region also includes two major railroad gateways, St. Louis and Memphis. Disruption to the rail network in the Mid-America region would require substantial traffic to be detoured, straining capacity on rail lines outside of the region and potentially affecting national commerce. A major disruption in the region would be costly, but is the risk sufficient to justify investment to prevent damage due to an earthquake?

Hazard Analysis of Railroad Infrastructure in the Mid-America Region

Geographic Information System Data and Methods

We developed probabilistic estimates of the railroad infrastructure potentially affected by an earthquake in the region using Geographic Information System (GIS) data. We used two rail databases, one from the U.S. Department of Transportation (USDOT) and another from a major railroad in the region. The USDOT database was used to quantify rail mileage and tonnage in the region, and the railroad s database was used as a basis to estimate the number and length of bridges in the region. Digital hazard maps prepared by the U.S. Geological Survey provided data on the location and probability of various PGA levels in the region. We used GIS software to perform an overlay of these data. This allowed us to quantify the extent of the railroad infrastructure exposed to various PGA levels (*6*).

Railroad Infrastructure

Two key elements of railroad infrastructure at risk in a major earthquake are track and bridges. Although roadbeds have suffered extensive damage in some locations due to previous earthquakes, railroad engineers generally believe that such damage can be repaired relatively quickly. The practicality and cost-effectiveness of upgrading roadbed is unclear. Research is currently underway to improve our understanding of roadbed instability due to ground motion and possible means of enhancing it (Tutumluer, unpublished data).

Railroad bridges have generally performed well in earthquakes, particularly compared to highway bridges (*7*). Railroad bridges tend to have more conservatively-sized foundations, superior bearing support conditions, large factors of safety in many structural components, and simply supported spans (*8*). The track structure also provides lateral and longitudinal resistance against seismic ground motion (*9,10*). Nevertheless, examples of railroad bridge failure do exist and railroad bridges in some areas exposed to seismic activity have been retrofitted to resist large ground motions (J. Craft, unpublished data)

Bridge response to ground motion is sometimes characterized using fragility curves that attempt to quantify the probabilistic relationship between PGA levels and bridge damage or failure (Hwang, unpublished data). Although such fragility curves have been developed for highway bridges they have not been developed for railroad bridges. Consequently, probabilistic estimates of railroad bridge failure under various earthquake scenarios are difficult to develop and subject to substantial uncertainty.

However, railroad bridge engineers have developed a consensus that PGA values greater than 20% g are considered likely to cause moderate damage, and greater than 40% g are likely to cause severe damage (Byers & AREMA Committee 9, unpublished data). These figures were used as the criteria for regions of interest in a hazard analysis of the Mid-America region s railroad infrastructure (*6*).

Hazard Analysis Results

There are 2,107 route miles with a 2% probability of experiencing PGA values greater than 20% g in the next 50 years. Comprehensive data on the number or size of railroad bridges in the region were not available. However, one of the major railroads, accounting for 14.2% of the mileage in the region, provided a comprehensive GIS database for their property. We determined the number of bridges per mile of rail line and the distribution of bridge lengths for this railroad. These statistics were combined with the USDOT rail GIS database to extrapolate railroad bridge estimates for the remaining railroads in the region. We estimate that there are 2,082 railroad bridges in areas potentially exposed to damaging PGA levels in the Mid-America region. The total length of these bridges is approximately 306,800 feet, or 58 miles. Railroad bridge engineers recently estimated the average replacement cost of bridges to be $2,100/track-foot (AREMA Committee 9, unpublished data). Based on this estimate, the replacement cost for all 2,082 bridges would be approximately $644,280,000.

To Retrofit or Not to Retrofit?

The question faced by railroads when considering these figures is whether or not to retrofit bridges to enhance their resistance to seismic damage. Even in a severe earthquake, only a fraction of the bridges in the region would be expected to fail. The bridges that actually suffered damage would be highly dependent on their location relative to the earthquake epicenter and local foundation conditions. The estimated PGA maps and other data provided by the USGS allow probabilistic estimates about the epicenter, magnitude, and consequent local ground motions that the bridges in the region are likely to experience. However, the lack of railroad bridge fragility curves precludes quantification of the number and location of bridges that might fail even if local ground motion probability distributions are known. Given the generally good performance of railroad bridges in the past and the size of the region, it is likely that only a small fraction would actually fail. Adopting a wait and see strategy for most railroad bridges in the region might be a rational approach.

Alternatively, railroads could retrofit some or all of their bridges in the region to reduce their probability of failure in an earthquake. Some options for retrofitting include: replacing bearings and anchor bolts with a more seismically resistant design, adding restraining devices to bridge spans, encasing piers, or increasing the size and stability of bridge footings (Foutch, unpublished data).

Based on several assumptions about size and design of bridges, and retrofit cost for bridge components, the total cost to retrofit all railroad bridges in areas capable of experiencing damaging ground motions is estimated to be $245,427,200 (*6*). Although lower than the replacement cost figure, it is still substantial, and the difficulty in predicting which bridges might actually fail complicates the decision to retrofit. The cost of retrofit, the generally satisfactory performance of railway bridges in past earthquakes, and the uncertainty about which bridges would actually benefit and how much, all argue against retrofitting small to medium-size bridges. Furthermore, even if a bridge was severely damaged or lost, railroads are generally capable of replacing short spans and small bridges quite rapidly (AREMA Committee 9 & Johnson, unpublished data). This ability for rapid replacement, combined with the large cost to retrofit railway bridges, suggests that it is more rationale to wait and see which bridges are actually damaged and then replace or repair those, rather than invest a large amount of money retrofitting thousands of bridges throughout the region.

However, replacing large trusses and lengthy deck truss spans characteristic of the major river-crossing bridges is another matter. Their repair would require long lead times for design, manufacturing, fabrication and delivery. The possibility of damage to multiple bridges could also mean a shortage of personnel, and potentially limit access needed for concurrent reconstruction of large bridges in the region. Therefore, we concentrated our analysis on the major river crossing bridges in the region. To evaluate the cost-effectiveness of retrofitting bridges in the region, we developed a cost analysis model (*6*).

Model Introduction

We estimated that there are 85 railway bridges greater than 500 feet in length exposed to substantial peak ground accelerations in the Mid-America region (*6*). Eight of these are major railroad river-crossing bridges critical to the rail network (Table 1). Several of these are near the center of the New Madrid seismic area, and are likely to experience severe PGA values in the event of a major earthquake. Our model development focused on scenarios involving these bridges; however, the methods are general and could be applied to large bridges in other regions as well.

The model uses a probabilistic net present value (NPV) analysis to compare the cost of retrofitting in current dollars, with the risk cost associated with not retrofitting (*11, 12)*. Values for several parameters are inserted into the model and it calculates an expected net present monetary value associated with retrofitting and not retrofitting. The difference in monetary value between retrofitting and not retrofitting the bridge is the risk cost associated with the decision. This risk value is compared to the cost of retrofitting to assess the decision to upgrade.

Model Parameters and Output

The model allows the user to input values for parameters related to the specific bridge in question. Model input variables include:

Earthquake probabilities (*13*)

Probability of Bridge Failure (estimated based on ground motion)

Repair Cost given Failure Type ($ per track foot) (AREMA 9, unpublished data)

Retrofit Cost ($ per bearing) (Dooley and Byers, unpublished data)

Detour Length (miles)

Time to Repair the Bridge (days)

Bridge Length (feet)

Detour Cost (including variable, fixed and lost revenue costs)

Annual Tonnage (MGT) (*5*)

Number of main spans and approach spans

The model uses the probability of bridge failure based on the probable local ground motions in the region in the decision process. Due to the lack of fragility curves for railroad bridges, the model uses the following scale to estimate seismic resistance gained by retrofitting:

PGA > 0.8 g ~ 25% reduction in failure probability

0.2 g > PGA > 0.8 g ~ 50% reduction in failure probability

0.05 g > PGA > 0.2 g ~ 75% reduction in failure probability

These are hypothetical values, solely for the purpose of testing and illustrating the model and its output. The model takes the input values for each of the input parameters and produces an expected monetary value of risk based on the maximum EMV criterion for retrofitting or not retrofitting the bridge. The monetary value of risk is compared with the cost of retrofit to determine the optimum alternative in the decision process.

If the bridge is retrofitted, the railroad has the immediate cost of retrofit. The retrofitted bridge will have greater resistance to ground motion, but this provides no benefit until an earthquake occurs causing ground motion sufficient to damage the bridge if it were not retrofitted. Thus, the benefit is the reduction in probability of failure, and in magnitude of damage to the bridge. If the retrofitted bridge is damaged, it is assumed the damage would be less severe on average, and thus the time to repair, and consequent detour cost would be lower. If the bridge is not retrofitted, then there is no immediate cost to the railroad. However, given a major earthquake, it is assumed that the probability of bridge failure and/or damage to the bridge would be higher. More time would be needed to repair the damaged structure, thus leading to higher detour costs. The higher detour costs result from having to use a longer route on the same railroad or the extra cost associated with detouring trains over another railroad.

Model Example Applied to the Mid-America Region

The eight major bridges of interest are in six different locations in the Mid-America region. If one of these major bridges is out of service, the railroad(s) using the bridge must find alternative routes for traffic. If a major earthquake occurred, a variety of network disruption scenarios are possible. One example of a potential network disruption in the Mid-America region is for the Canadian National-Illinois Central (CN-IC) main line from Chicago to New Orleans. From north to south, a single line extends south from Chicago and splits into two lines at Edgewood, Illinois. These two lines rejoin at Fulton, Kentucky and a single line continues south to Memphis (Figure 3). Both main lines cross the Ohio River, with the western line crossing at Cairo, Illinois on a bridge owned by CN-IC, and the eastern line crossing at Metropolis, Illinois via trackage rights on a bridge owned by Burlington Northern Santa Fe (BNSF). A major earthquake could put one or both of these bridges out of service for an extended period of time. If only one of these bridges were lost, and assuming there was adequate capacity, the CN-IC railroad could probably detour most of its traffic over the other. In this case, there would be no substantial detour cost for shifting the traffic to the line still in service, since it is owned by the CN-IC railroad (Figure 4A).

However, if both of the bridges the CN-IC uses were put out of service, the CN-IC railroad would need to detour its traffic over another railroad. Line capacity permitting, the shortest detour would likely be the best option. In this example, the shortest detour for the CN-IC is over the Union Pacific (UP) and BNSF. The CN-IC has an interchange with the UP at Tamaroa, Illinois. Use of this connection would allow the CN-IC to cross the Mississippi River on UP trackage at Thebes, Illinois, connect with the BNSF at Rockview, Missouri and return to their own tracks at Memphis, Tennessee (Figure 4B). In this case, the detour mileage over the UP and BNSF is 250 miles. However, the UP s line from Tamaroa to Chester is a light density line that would need to be upgraded to handle the increase in tonnage for any extended period.

Due to the location of the two CN-IC bridges and the UP bridge, all of which are in areas with a high probability of experiencing severe PGA values (> 40% g), a third scenario is possible. If the Union Pacific bridge at Thebes, Illinois were also to suffer damage, along with the Metropolis and Cairo Bridges, all three bridges could be out of service for an extended period of time (Figure 4C). In this situation, the shortest route for the CN-IC is to use their line from Gilman, Illinois to Springfield, Illinois, and then use trackage rights on Union Pacific from Springfield to St. Louis, MO. After reaching St. Louis, CN-IC traffic would use the BNSF line to Memphis, Tennessee, and then return to their mainline. In this case, the detour mileage over the BNSF is 278 miles.

The scenario described above assumes adequate capacity being available to handle the increase in traffic over the alternate lines. Some of the factors affecting the capacity of rail lines include (Salzman, unpublished data):

- Track speed
- Traffic type (average and variability in train speeds and lengths)
- Traffic control system
- Distance between sidings (single track)
- Percent grade and maintenance cycles
- Level of service provided

Sufficient extra capacity may not exist on some of the routes that would be used for rerouting. A more thorough capacity analysis would need to be completed to determine if the detour routes could handle the increase in traffic.

For the above example, the model was used with the input parameters appropriate to the scenario to determine the EMV risk cost. Presumably, CN-IC s best option is to retrofit one of the two bridges on their mainlines to reduce the probability of damage given a major earthquake. This would allow CN-IC to keep traffic on their lines as much as possible, capacity permitting. We assumed that CN-IC would choose to retrofit the Metropolis bridge because: 1) it handles more traffic, 2) it is shorter and 3) it is in a lower ground motion area (meaning a higher seismic resistance gained by retrofitting). CN-IC provided data on the number of approach spans and main spans for the bridge at Metropolis (Luciano, unpublished data).

The results of these three scenarios are presented in Table 2. If the risk cost exceeds the retrofit cost, retrofitting railway bridges might be more cost-effective. Of these three, only the longest detour (280 miles) combined with the longest repair time (1,500 days) resulted in a scenario in which retrofitting appeared to be cost-effective. To further understand if there might be plausible combinations of circumstances in which retrofitting was rational we conducted a sensitivity analysis using the model.

Model Sensitivity Analysis

The variables evaluated in the sensitivity analysis were: 1) time to repair for an F_1 type failure and 2) detour mileage. The remaining input parameters were held constant using data for the Metropolis, Illinois bridge:

Repair cost:	F_1 type failure = $2,100/track foot
	F_2 type failure = $700/track foot
Retrofit cost:	Main span bearing = $65,000/bearing
	Approach span bearing = $15,000/bearing

Bridge length = 5,660 feet

Number of main spans = 7

Number of approach spans = 39

Discount rate for NPV analysis = 5% (*14*)

Annual tonnage = 50 MGT

Time to repair F_2 type failure = 30 days

Various increased transportation costs (fixed and variable costs and lost revenue)

The results indicated that for certain combinations of detour length and time-to-repair (for an F_1 type failure), retrofitting is cost-effective (Figure 5) although the values were fairly high.

The solid horizontal line represents the retrofit cost of the CN-IC Metropolis bridge. The intersection point between the horizontal line, representing retrofit cost, and the sloping lines, representing increasing detour length, is the point where the risk cost exceeds the retrofit cost. Any point along the increasing detour length lines above the horizontal retrofit cost line represents a detour length and time-to-repair combination where retrofitting is cost-effective. The results show that when the detour length is short and the time-to-repair is small, it is not cost-effective to retrofit. As the detour length and repair time increase, the cost-effectiveness of retrofitting becomes plausible. Analyzing this example, for detour lengths up to 400 miles, the F_1 time to repair must be 1,080 days or greater for retrofitting to be cost-effective.

Bearings are considered to be the most important railroad bridge element requiring retrofit, and for this sensitivity analysis, bearings were the principal cost element considered. However, if other options for retrofitting were also employed (such as encasing piers, increasing footing sizes, etc.), the cost to retrofit would increase. This would increase the horizontal line in Figure 5, thereby increasing the threshold repair time for retrofitting to be cost-effective. However, these would also have the effect of reducing the probability of failure, thereby increasing the benefit of retrofitting. If the discount rate increased, the NPV of the risk cost would also be reduced, so this too, would increase the necessary time to repair for retrofitting to be cost-effective. Higher transportation costs on the other hand, would tend to reduce the threshold. This could be in the form of higher annual tonnage on the route, or higher detour costs per ton or per train.

Recommendations for Further Study

The completion of this study has provided a better understanding of the railroad infrastructure potentially at risk in a major earthquake. However, many assumptions had to be made due to incomplete information concerning railway bridges exposed to seismic activity. The findings here must be considered in light of these limitations. Based on what we learned we recommend that additional information would be beneficial to record when railroad bridges are involved in earthquakes including the following:

Information on the bridge components that fail (such as the number and type of bearings, spans, trusses and piers that fail) to aid in the development of railroad bridge fragility curves.

Information on the bridge components that may have benefited from retrofitting. Estimate the forces exerted on individual bridge components and the amount of resistance or added strength that might be gained from various retrofit options.

Determine and record the local ground motion characteristics near and around affected railway bridges. Detailed ground motion information for each abutment, pier and span would help in better understanding the local variability in ground motion and the consequent effects on bridges and supports.

The effects of liquefaction near and around railway bridges experiencing seismic activity and the resultant damage to bridge components.

The number of railway bridges that experience damage compared to the total number of bridges in the affected area. Also, establish a general PGA damage scale for railroad bridges.

A recent study by Otter and Prucz (*15*) provides additional insight into some of these questions. Further documentation and analysis of critical information such as this will allow the railroad bridge engineering community to refine its understanding of the impact of seismic activity in general and in the Mid-America region in particular. The accumulation of such data will enable railroads to better estimate the risk to the rail network given a major Mid-America earthquake and the benefits and costs associated with various options to mitigate these risks.

CONCLUSIONS

The Mid-America region has an important place in the US rail network. Within the region approximately 2,107 route miles of trackage representing about 2.2% of the national total is exposed to potentially damaging peak ground accelerations (2% probability of experiencing greater than 20%g in the next fifty years). Furthermore there are a number of high-tonnage lines in the region including several with annual traffic levels greater than 60 MGT. The total gross ton-mileage in 1999 for rail lines in the region was 96.2 billion, which represented 3.2% of the U.S. total. By extrapolating the data for a major railroad in the region we estimated that the total length for all bridges in areas potentially exposed to damaging PGA levels was approximately 306,800 feet (58 miles). Among these are eight bridges across the Ohio and Mississippi Rivers that carry approximately 245 million revenue tons of freight per year, accounting for 11.4% of the national total rail freight originated in the U.S.

We developed a model to determine the cost-effectiveness of retrofitting railroad bridges. The input parameters for the model include: repair cost per failure type, bridge length, number of approach spans, number of main spans, annual tonnage, detour length, time to repair per failure type, and discount rate for net present value analysis. In general, it appears that retrofitting small to medium-sized bridges is not cost-effective because of the good performance of railroad bridges in past earthquakes, the uncertainty about which bridges would actually be affected by an earthquake, and the ability of railroads to relatively quickly repair or replace shorter span bridges. However, a sensitivity analysis based on data for the Ohio River bridge at Metropolis, IL indicated that for large, strategically important bridges with a high concentration of traffic there are plausible scenarios for which retrofitting might be rational.

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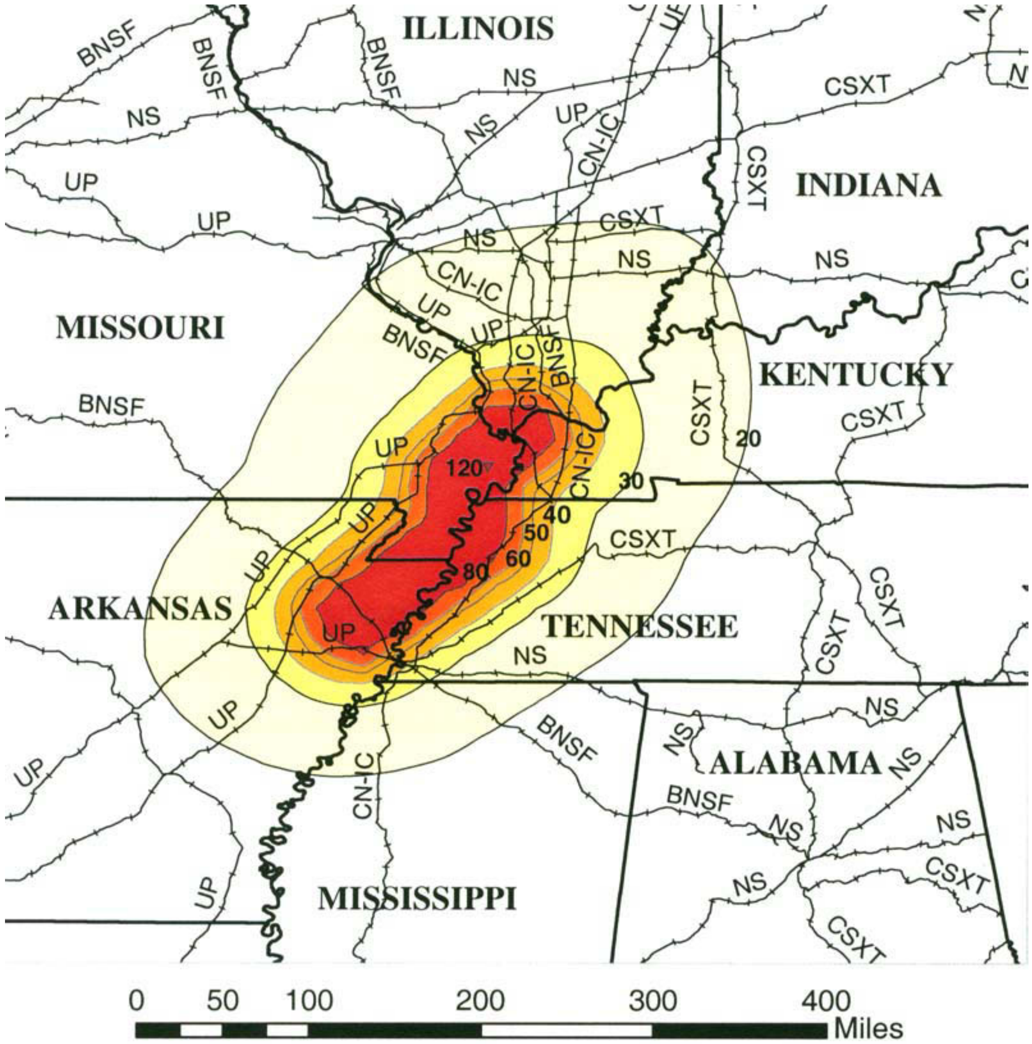

FIGURE 1 Mid-America Rail Lines and Peak Ground Acceleration (PGA) Contours (in Percent Gravity or "g") with a 2% Probability of Occurrence in the Next 50 Years. PGA Levels Greater than 20%g Are Thought to be Capable of Damaging Railroad Bridges.

A

B

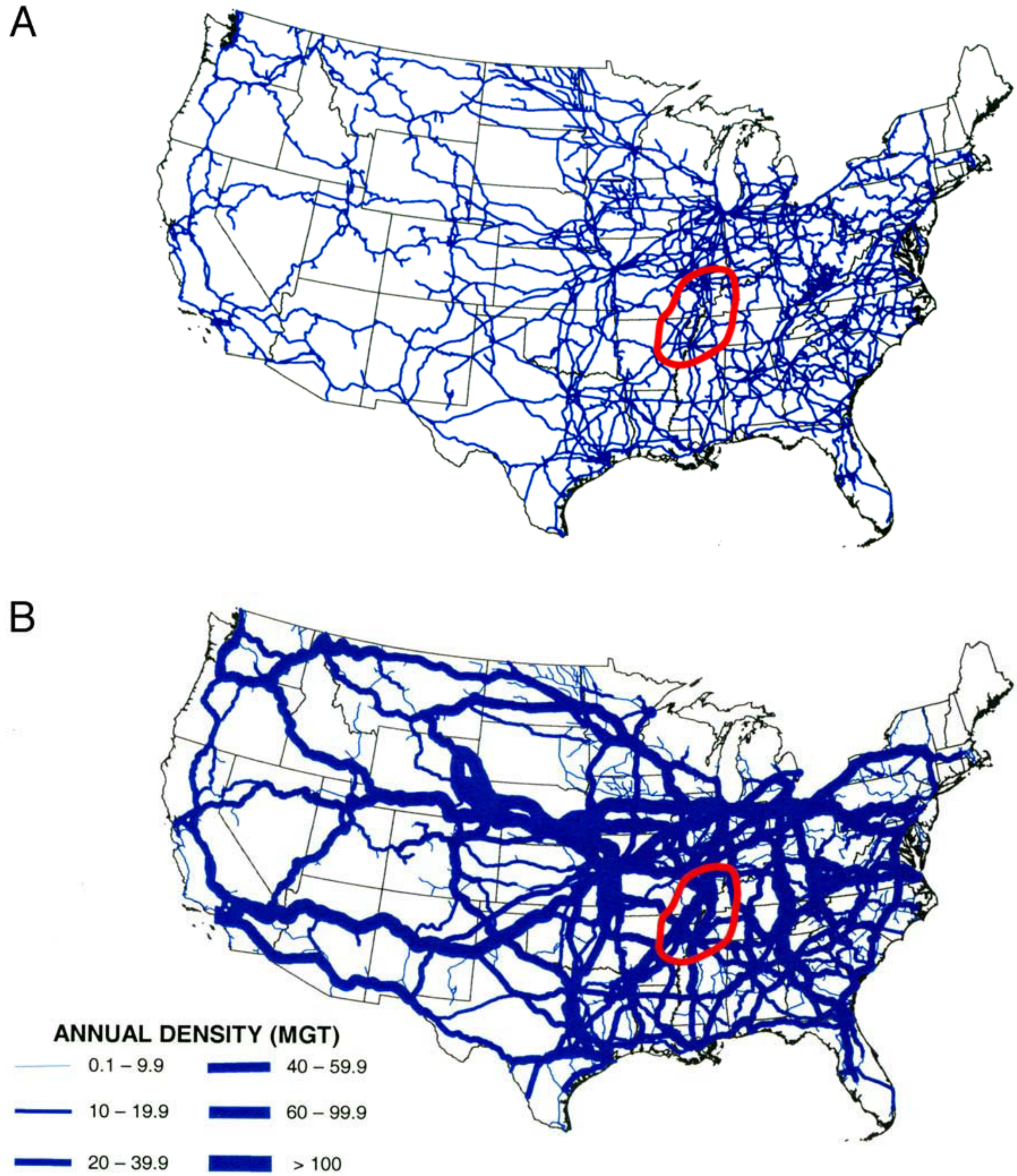

FIGURE 2 A) United States Railroad Network With the Potentially Damaging Motion Ground-Motion Contour (>20%g) B) With Traffic Density in Million Gross Tons

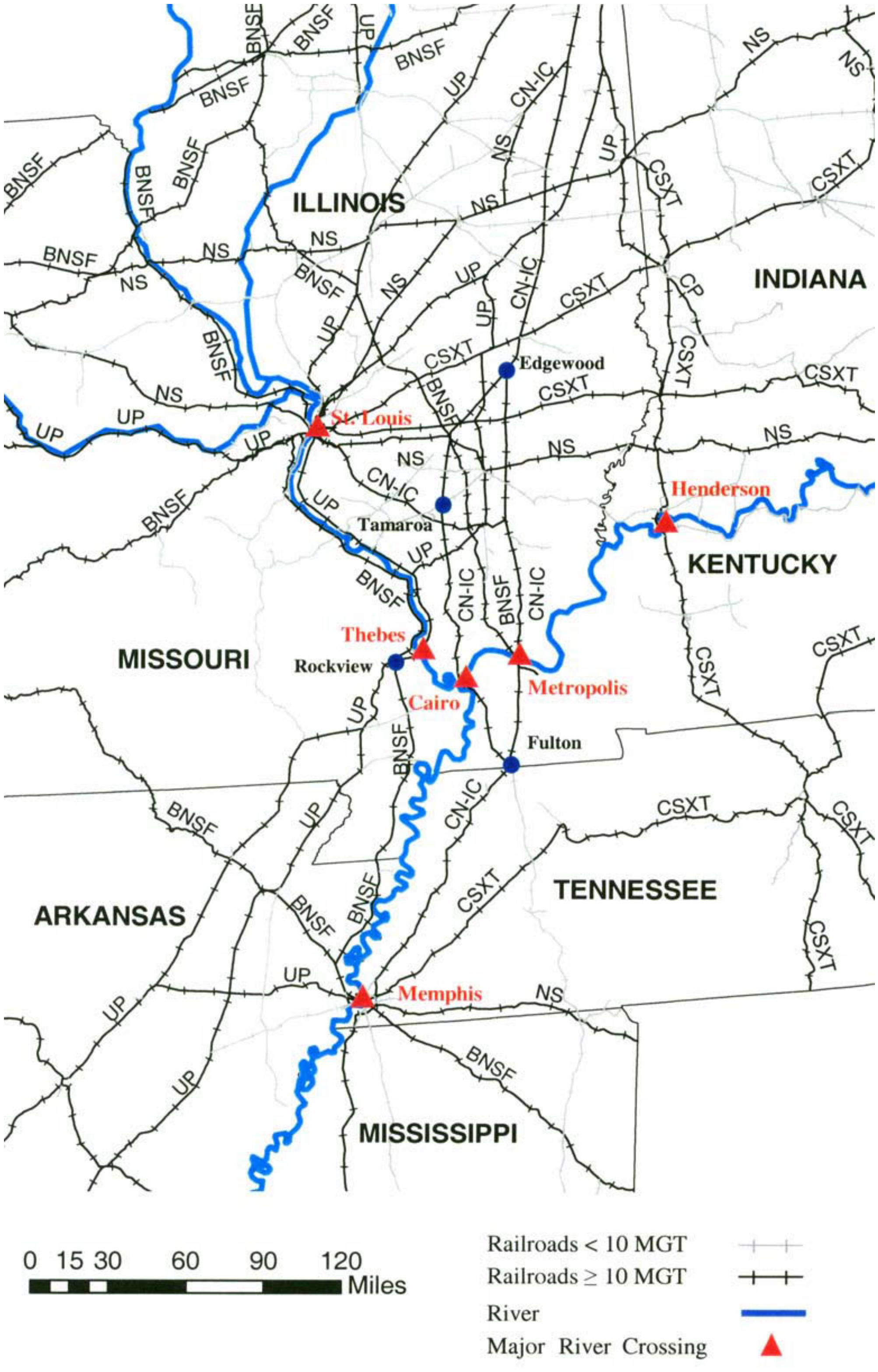

FIGURE 3 Map of Railroad Lines in the Mid-America Earthquake Region Showing the Location of Major Bridges Crossing the Ohio and Mississippi Rivers

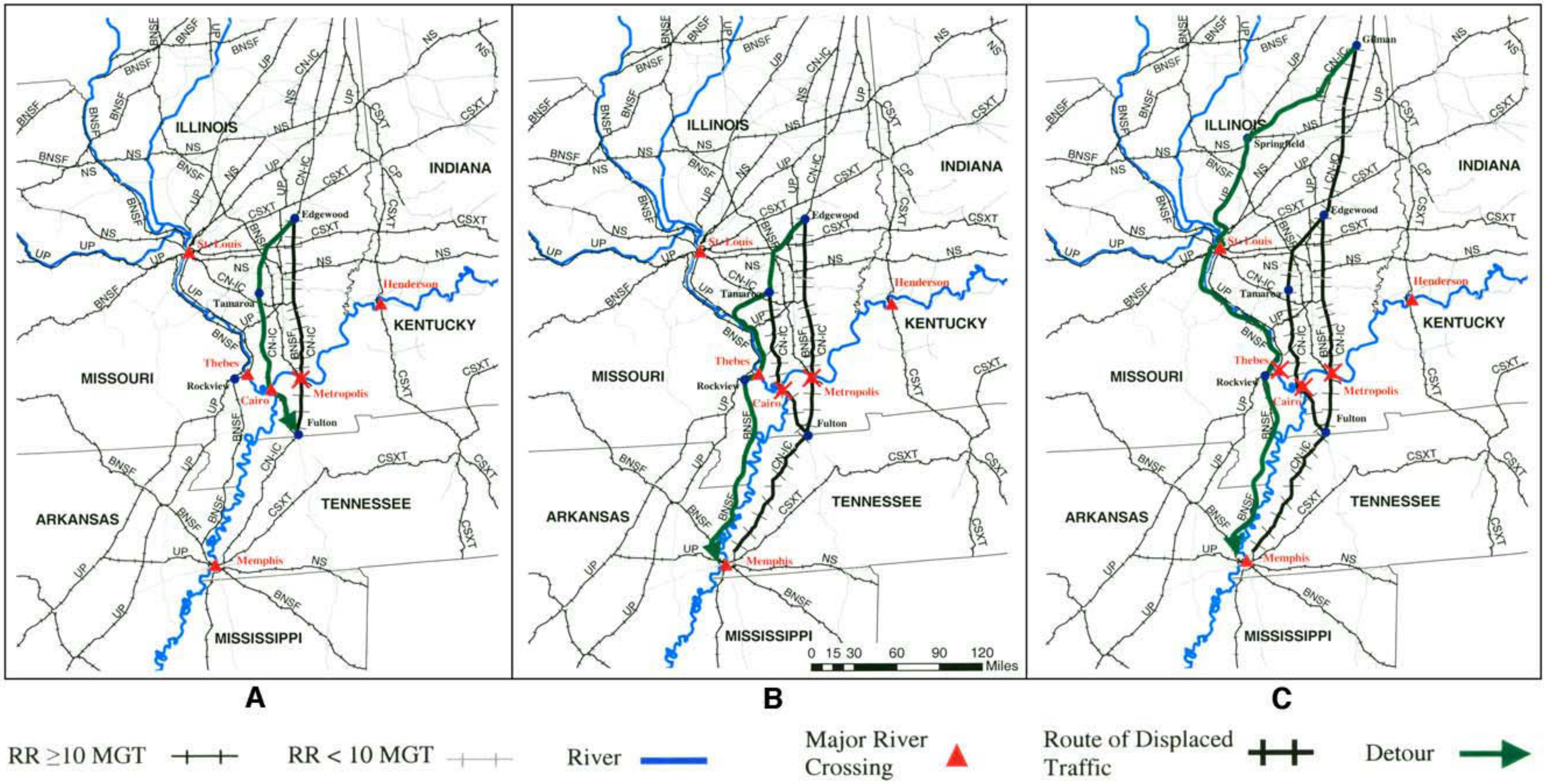

FIGURE 4 Possible Detour Scenarios for Traffic on the CN-IC:
A) With the Metropolis Bridge Out of Service B) With the Metropolis and Cairo Bridges Out C) With the Metropolis, Cairo and Thebes Bridges Out

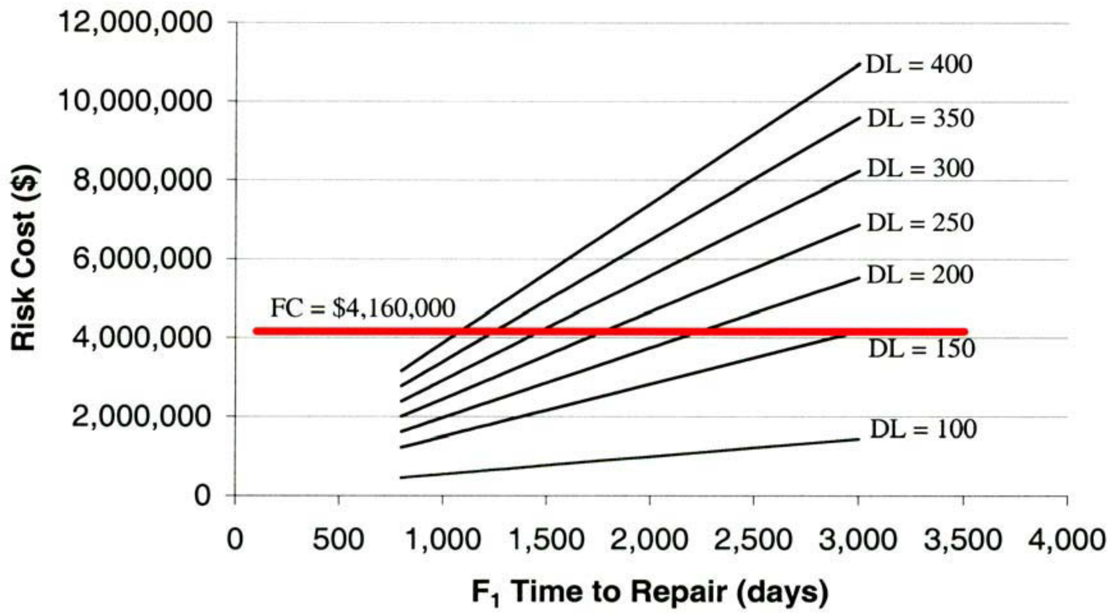

FIGURE 5 Sensitivity Analysis for the CN-IC Metropolis Bridge Scenario
(DL = Detour Length (in miles) and FC = Estimated Retrofit Cost)

TABLE 1 Major Railroad River Crossing Bridges in the Mid-America Region

Railroad	River	Location	Density (MGT)	2% PGA
CN-IC	Ohio	Cairo, IL	40	0.90
Union Pacific	Mississippi	Thebes, IL	95	0.80
BNSF (CN-IC)	Ohio	Metropolis, IL	50	0.60
BNSF	Mississippi	Memphis, TN	65	0.40
Union Pacific	Mississippi	Memphis, TN	99	0.40
CSXT	Ohio	Henderson, KY	60	0.25
TRRA	Mississippi	St. Louis, MO	50	0.25
TRRA	Mississippi	St. Louis, MO	50	0.20

TABLE 2 Cost-Analysis Model Output from CN-IC Example Scenarios

Detour Length (miles)	Time to Repair (days)	EMV Risk Cost ($)		Risk Cost ($)	Retrofit Cost ($)	Risk - Retrofit ($)
		Retrofit	No Retrofit			
70	F_1=365 F_2=14	492,120	815,294	323,174	4,160,000	-3,836,826
250	F_1=750 F_2=28	2,986,536	4,872,563	1,886,026	4,160,000	-2,273,973
280	F_1=1,500 F_2=90	6,735,651	11,071,406	4,335,755	4,160,000	175,755