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Model for Evaluating Cost-Effectiveness of Retrofitting Railway Bridges for Seismic Resistance

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Many of the major railroad lines in the Mid-America earthquake region are potentially susceptible to high peak ground accelerations (PGA) and soil liquefaction effects due to an earthquake associated with the New Madrid fault. With geographic information systems (GIS) data and analysis techniques, the risk to the rail network posed by a major earthquake in the region was estimated. It was estimated that about 2,107 active rail route miles and 2,082 railroad bridges, including eight major river-crossing bridges over the Ohio and Mississippi Rivers, are in areas with a 2% probability of experiencing PGA values with potential to cause moderate to severe damage (>20% *g*) in the next 50 years. Because of the importance of this portion of the rail network and the bridges in the region, a model to calculate the cost-effectiveness of retrofitting railway bridges for enhanced seismic resistance was developed. Analysis using the model indicates that retrofitting small to moderately sized bridges is not generally cost-effective in the Mid-America region. However, a sensitivity analysis indicated that for large river-crossing bridges there may be plausible conditions when retrofitting would be cost-effective.

During a 5-month interval in the winter of 1811–1812, more than 2,000 earthquakes occurred in a region near the confluence of the Mississippi and Ohio rivers near the town of New Madrid, Missouri. Between six and nine of these earthquakes are believed to have 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 backward. This created numerous waterfalls and caused widespread soil liquefaction throughout the area. Analysis of historical and geological data indicates that these earthquakes were not isolated events. Strong earthquakes have occurred repeatedly in the New Madrid region and it continues to have the highest level of seismic activity in the United States east of the Rocky Mountains (*2*) with over 4,600 low-magnitude earthquakes recorded since 1974 (*3*).

When the next major Mid-America earthquake occurs, the potential losses in the region are expected to be substantial because many of the structures in the region were not designed to be seismically resistant, there is poor soil foundation material in the area, and the size of the potentially affected area is large (*4*). 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 mi^2 of the region, and PGA values exceeding 40% *g* over an area of 9,647 mi^2 (Figure 1). Railroad bridge engineers [American Railway Engineering and Maintenance-of-Way Association (AREMA) Committee 9 and W. G. Byers, unpublished work] believe PGA values between 20% and 40% *g* are capable of causing moderate damage to railroad bridges, and PGA values exceeding 40% are capable of causing severe damage. These factors, coupled with knowledge gained from past earthquakes, indicate that the railroad system in the Mid-America region may be vulnerable to damage from a large earthquake.

IMPORTANCE OF RAIL NETWORK IN MID-AMERICA REGION

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

Two major waterways, the Mississippi and Ohio Rivers, traverse the region and much of the nation's rail traffic traveling through the central United States must cross one or both of these rivers. Eight major bridges, five over the Mississippi River and three over the Ohio River, carry about 245 million tons of revenue freight per year (*5*), accounting for 11.4% of the freight tons originated in the United States annually. The region also includes two major freight railroad gateways, St. Louis and Memphis. These gateways serve as large classification facilities for sorting and interchanging rail traffic moving between eastern and western railroads. 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 the nation's commerce. A major disruption in the region would be costly. Is the risk sufficient to justify investment in the rail infrastructure to prevent damage due to an earthquake?

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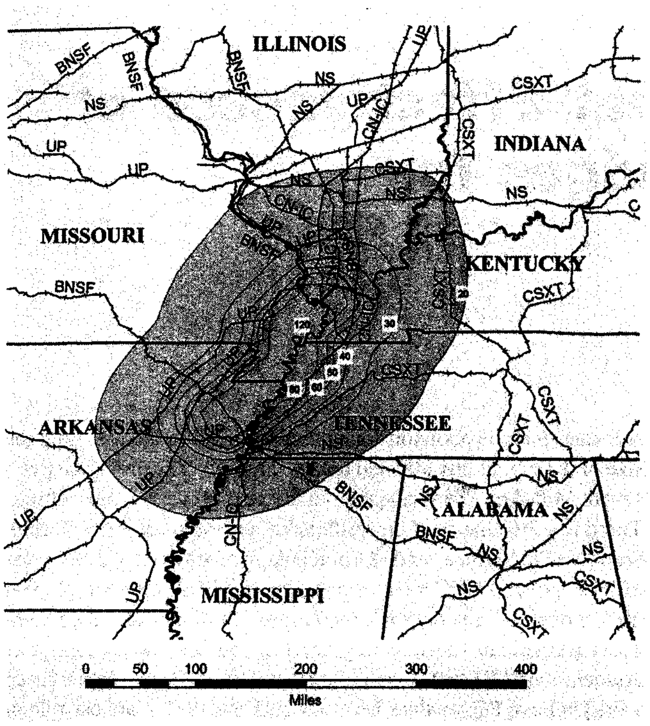

FIGURE 1 Mid-America rail lines and PGA contours (in *g*) with a 2% probability of occurrence in the next 50 years. PGA levels >20% *g* are thought to be capable of damaging railroad bridges.

HAZARD ANALYSIS OF RAILROAD INFRASTRUCTURE IN MID-AMERICA REGION

Geographic Information System Data and Methods

The first step was to develop probabilistic estimates of the railroad infrastructure potentially affected by an earthquake in the region by using geographic information system (GIS) data. Two rail databases were used, 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 for the region prepared by the U.S. Geological Survey provided data on the location and probability of various PGA levels. GIS software was used to perform an overlay of these data. This made it possible to quantify the extent to which features of the railroad infrastructure were exposed to various PGA levels, most notably rail route mileage and bridges (*6*).

Railroad Infrastructure

The two key elements of railroad infrastructure at risk in a major earthquake are track and bridges. Although roadbeds have suffered locally extensive damage in previous earthquakes, railroad engineering professionals generally believe such damage can be repaired relatively quickly. More research is needed on the methods and potential benefits of enhancing railroad track and roadbed stability in earthquakes; however, roadbeds are unlikely to be the cause of lengthy rail traffic disruptions. Consequently, the retrofitting analysis concentrated on bridges.

Railroad bridges generally have performed well in past earthquakes, particularly compared with highway bridges (*7*). This is because railroad bridges tend to have conservatively sized foundations, superior bearing support conditions, and large factors of safety in many structural components, and most have simply supported spans (*8*). The track structure also provides lateral and longitudinal resistance against seismic ground motion (*9–12*). Nevertheless, examples of railroad bridge failure do exist and railroad bridges in some areas exposed to seismic activity have been retrofitted to resist high ground motions (J. Craft, unpublished data).

Bridge response to ground motion is sometimes characterized with fragility curves that attempt to quantify the relationship between PGA levels and the probability of bridge damage or failure. 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 predict and are subject to substantial uncertainty. However, railroad bridge engineers have developed a consensus that PGA values >20% *g* are considered likely to cause moderate damage, and values >40% *g* are likely to cause severe damage (W. G. Byers and 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 mi with a 2% probability of experiencing PGA values >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 major railroad that accounts for 14.2% of the mileage in the region provided a comprehensive GIS database for its own property. These data were used to develop statistical estimates of the number of bridges per mile of rail line and the distribution of bridge lengths (*6*). These statistics were used with the USDOT rail GIS database to extrapolate estimates for the entire region. It is estimated that there are 2,082 railroad bridges in areas potentially exposed to damaging PGA levels in the Mid-America region. The estimated total length of these bridges is about 306,800 ft or about 58 mi. Estimates of the replacement cost for small to moderately large-sized railroad bridges range from $2,000 to $4,000 per lineal track-ft (AREMA Committee 9, unpublished data) (for a very large bridge they may be as high as $25,000 to $30,000 per track ft). Based on these figures, it is estimated that the replacement cost for all the bridges in the region (excluding the very largest ones) would range from $0.6 billion to $1.2 billion.

Retrofit or No Retrofit?

The question faced by railroads when considering these figures is whether 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. Which bridges actually suffer 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 U.S. Geological Survey allow probabilistic estimates about the epicenter, magnitude, and consequent local ground motions the bridges in the region are

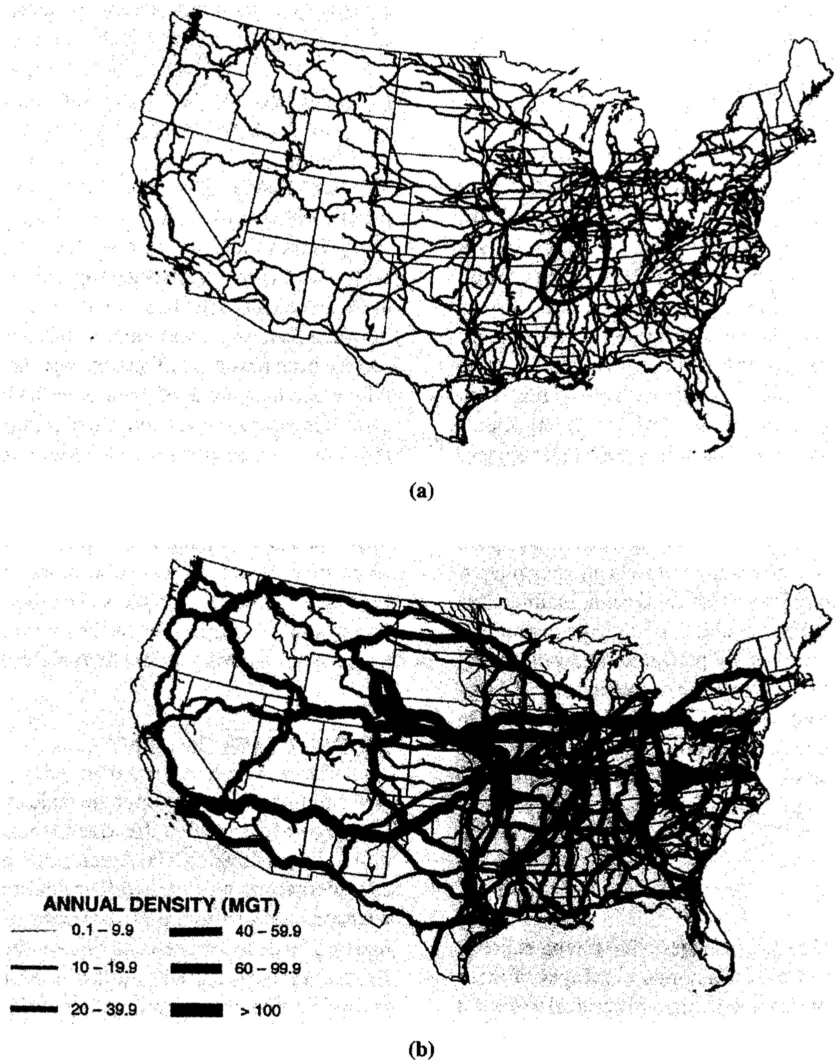

FIGURE 2 U.S. railroad network: (*a*) with potentially damaging ground-motion contour (>20% *g*); (*b*) with traffic density in MGT.

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, and increasing the size and stability of bridge footings (D. Foutch, unpublished data).

To estimate the total retrofit cost for all the railroad bridges in the region, the following assumptions were made:

- Bridge spans are simply supported.
- Each span rests on four bearings.
- Each pier supports four bearings.
- Each abutment supports two bearings.
- Average span length is about 75 ft.
- The preferred retrofit method is to replace bridge bearings with designs that are more seismically resistant.

It is also assumed that railroad bridge spans <100 ft long are generally girder spans and bridge spans >100 ft are usually truss spans. Although there are likely many exceptions, these figures represent averages and should suffice for developing rough cost estimates for the region. From the hazard analysis, it is estimated that the average bridge length in the region is 147 ft (*6*). Assuming most of the bridge spans in the region are girder spans, the average bridge length was divided by two and an average span length of about 75 ft was used to determine the total retrofit cost. The cost to retrofit bearings on a typical 100-ft simple span is estimated to be $15,000 per bearing (M. Dooley, unpublished data). The following expression was used to estimate the cost associated with retrofitting all the railway bridges in areas capable of experiencing damaging PGAs:

$$\text{Total retrofit cost} = S \times B \times BC$$

where

S = total number of bridge spans,
B = number of bearings per span, and
BC = retrofit cost per bearing.

The total cost to retrofit all railroad bridges in areas capable of experiencing damaging ground motions is estimated at about $250 million. Although lower than the replacement cost figure, it is still substantial, and the difficulties in predicting which bridges might actually fail complicate the decision to retrofit. The cost to retrofit, the generally satisfactory performance of railway bridges in past earthquakes, and the uncertainty about which bridges would actually benefit all argue against retrofitting small to medium-sized bridges. Furthermore, railroads are generally capable of replacing short spans and small bridges quite rapidly (AREMA Committee 9 and M. Johnson, unpublished data). This ability for rapid replacement, combined with the large cost to retrofit railway bridges, makes railroads less concerned about short to medium-sized bridges.

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 could limit access needed for concurrent reconstruction of large bridges in the region. Therefore, analysis of the railway bridges in the region concentrates on the major river crossings. To examine the large river-crossing bridges in the region, a model was developed to determine the cost-effectiveness of upgrading these railway bridges.

MODEL INTRODUCTION

It is estimated that there are 85 railway bridges >500 ft long exposed to substantial PGAs in the Mid-America region (*6*). Eight of these major railroad river-crossing bridges are particularly critical to the rail network (Table 1). Several are near the center of the New Madrid seismic area and are likely to experience severe PGAs in the event of a major earthquake. Model development concentrated on scenarios involving these bridges; however, the methods are general and could be applied to other large railway bridges in the region and elsewhere.

The model can be used as an aid in determining the cost-effectiveness of upgrading railway bridges. It uses a probabilistic net present value (NPV) approach to compare the cost of retrofitting in current dollars with the risk cost associated with not retrofitting. Input parameter values are inserted into the model and it produces an expected net present monetary value associated with retrofitting the bridge and not retrofitting the bridge. The difference in monetary value between retrofitting and not retrofitting is the risk associated with the decision. This risk value can be compared with the cost of retrofitting to assess the decision to upgrade.

When considering whether to retrofit major bridges, railroads are faced with a set of probabilistic choices and economic risks. If the bridge is retrofitted, the railroad incurs the cost of retrofit and gains a bridge with greater resistance to ground motion. However, this provides no benefit to the railroad unless and until an earthquake occurs in which there is ground motion sufficient to damage the bridge if it had not been retrofitted. Thus, the benefit is the reduced probability of failure and magnitude of damage to the bridge. If the bridge is damaged, it is assumed that a retrofitted bridge would require less time for repair and thus there would be a lower cost of detouring traffic over alternative routes. If the bridge is not retrofitted, the railroad has no immediate cost. However, given a major earthquake, it is assumed there is a higher probability of bridge failure or damage to the bridge. 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 DEVELOPMENT

Determining whether to upgrade major railway bridges is a decision for the owner. Is it cost-effective to retrofit the bridge given current probability estimates? To develop the model, a decision tree with two alternatives was created. The decision tree is a visual aid for the decision process (Figure 3). It consists of decision nodes and chance nodes. The decision node (square) in the model provides two alternatives: to retrofit or not retrofit. After an alternative is chosen, the possible outcomes stemming from that alternative are represented by chance nodes (circles).

Chance Nodes A and B account for the exceedance probabilities of various ground motions. An example is the probability of exceeding 0.4 g (40% g) ground motion equals 0.03 [$P(\text{Exd } 0.4\ g) = 0.03$]. Chance Nodes 1 through 8 account for the failure probability of the bridge given that it was retrofitted or not retrofitted. An example is the probability of an F_1-type bridge failure given the bridge is retrofitted is 0.53 [$P(F_1\&R) = 0.53$]. The outcomes from each chance node are mutually exclusive and collectively exhaustive (*13*); thus,

TABLE 1 Major Railroad River Crossing Bridges in 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

NOTE: CSXT = CSX Transportation; TRRA = Terminal Railroad Association of St. Louis.

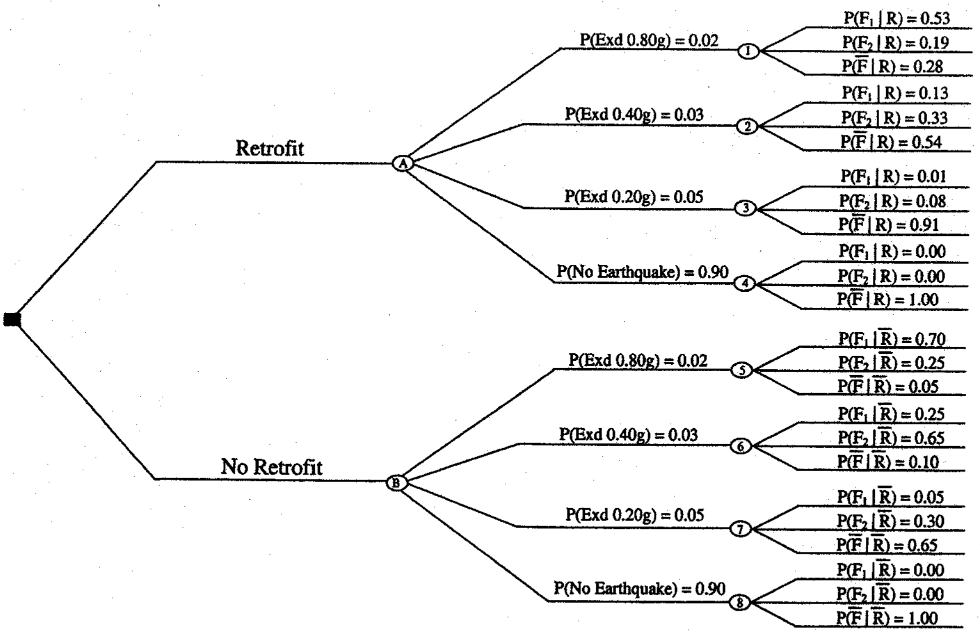

FIGURE 3 Decision tree for analyzing the option to retrofit versus not retrofit.

the probabilities associated with each branch stemming from the chance nodes must add up to 1.

Two types of bridge failure are defined for the model. An F_1-type failure is defined as a bridge having major damage. For an F_1-type failure, the time to repair and cost to repair are substantial. An F_2-type failure is defined as a bridge having minor to medium damage. For an F_2-type failure, the time to repair is minimal depending on the damaged bridge components. A bridge having no measurable damage is denoted by *F*-bar.

In decision analysis, the objective is to make the best decision (*13*). For this model, the utility values are stated in terms of the respective probabilities for each alternative. Because alternatives can be expressed in monetary value, the model uses the maximum expected monetary value (EMV) criterion, discounted to determine the NPV of the risk associated with retrofitting and not retrofitting. The NPV approach discounts future net benefits and costs to their present value (*14*). The NPV approach is used in the model because it reduces the stream of future costs associated with retrofitting and not retrofitting into a single comparable cost. The difference between the NPV values of risk for retrofitting and not retrofitting is then compared with the cost of retrofitting the bridge to determine the optimal alternative. The optimum alternative is the one whose EMV is

$$d(a_{\text{opt}}) = \max_i \left\{ \sum_j p_{ij} d_{ij} \right\}$$

where

$d(a_{\text{opt}})$ = optimal alternative,
d_{ij} = monetary value of the jth consequence associated with alternative i, and
p_{ij} = corresponding probability.

This approach allows the decision maker to systematically weigh the value of each outcome by the corresponding probability (*13*).

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 the following:

- Earthquake probabilities (*15*),
- Probability of bridge failure (estimated based on ground motion),
- Repair cost given failure type (dollars per track foot) (AREMA 9, unpublished data),
- Retrofit cost (dollars per bearing) (M. Dooley and W. G. 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*), and
- 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. Because of 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, and
- 0.05 *g* < PGA < 0.2 *g* ~ 75% reduction in failure probability.

These are purely 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 EMV 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.

MATHEMATICAL EXPRESSION OF COST-EFFECTIVENESS MODEL

The cost-effectiveness decision criteria and model are as follows:

It is cost-effective to retrofit the bridge if $B > FC$

where

B = risk cost = $K_1 - K_2$,
FC = retrofit cost,

$$K_1 \sum_{k=1}^{4} \sum_{i=0}^{50} D_1 \times d_i \times S_k = \text{NPV of cost if retrofitted,}$$

$$K_2 \sum_{k=1}^{4} \sum_{i=0}^{50} D_2 \times d_i \times S_k = \text{NPV of cost if not retrofitted,}$$

D_1 = expected value of the cost associated with an event, with retrofit,
$= P(F_1|R)(DC_{F_1}T_{F_1} + RC_{F_1}) + P(F_2|R)(DC_{F_2}T_{F_2} + RC_{F_2}) + P(F_0|R)(DC_{F_0}T_{F_0} + RC_{F_0})$,
D_2 = expected value of the cost associated with an event, without retrofit,
$= P(F_1|R_0)(DC_{F_1}T_{F_1} + RC_{F_1}) + P(F_2|R_0)(DC_{F_2}T_{F_2} + RC_{F_2}) + P(F_0|R_0)(DC_{F_0}T_{F_0} + RC_{F_0})$,
d_i = discount factor from year 0 to year 50,
S_k = exceedance (Exd) probability per year for *k*th scenario [when $k = 1$, $S_1 = P(\text{Exd } 0.8\ g)/50$; $k = 2$, $S_2 = P(\text{Exd } 0.4\ g)/50$; $k = 3$, $S_3 = P(\text{Exd } 0.2\ g)/50$; $k = 4$, $S_4 = P(\text{no earthquake})$],
$F_0 = \bar{F}$ = no measurable damage,
F_1 = bridge failure with major damage,
F_2 = bridge failure with minor to medium damage,
R = retrofit,
$R_0 = \bar{R}$ = no retrofit,
DC_j = detour cost per *j*th failure type ($j = 0$, F_0 failure type, etc.),
T_j = time to repair per *j*th failure type, and
RC_j = bridge repair cost per *j*th failure type.

MODEL EXAMPLE APPLIED TO 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.

Three Bridge Damage Scenarios

An example of a potential network disruption in the Mid-America region is for the Canadian National–Illinois Central (CN-IC) mainline 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 4). Both mainlines 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, it is presumed that the detour costs would not be substantial because the alternative route is owned by the CN-IC, and the mileage is about the same (Figure 5*a*).

However, if both of the bridges the CN-IC uses were put out of service, traffic would need to detour 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 its own tracks at Memphis, Tennessee (Figure 5*b*). In this case, the

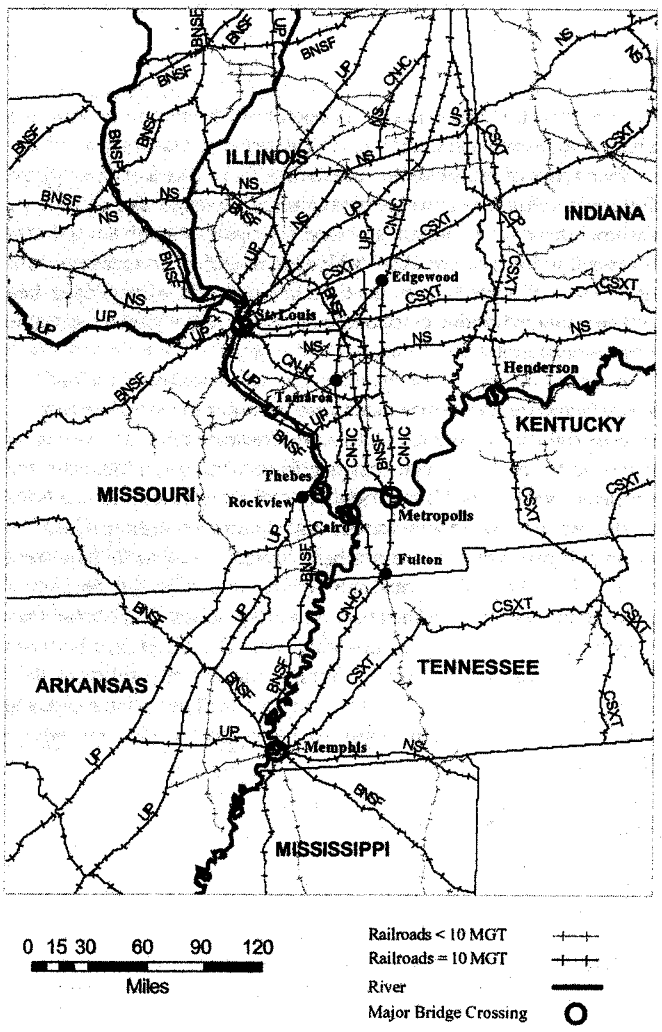

FIGURE 4 Map of railroad lines in the Mid-America earthquake region showing location of major bridges crossing Ohio and Mississippi Rivers.

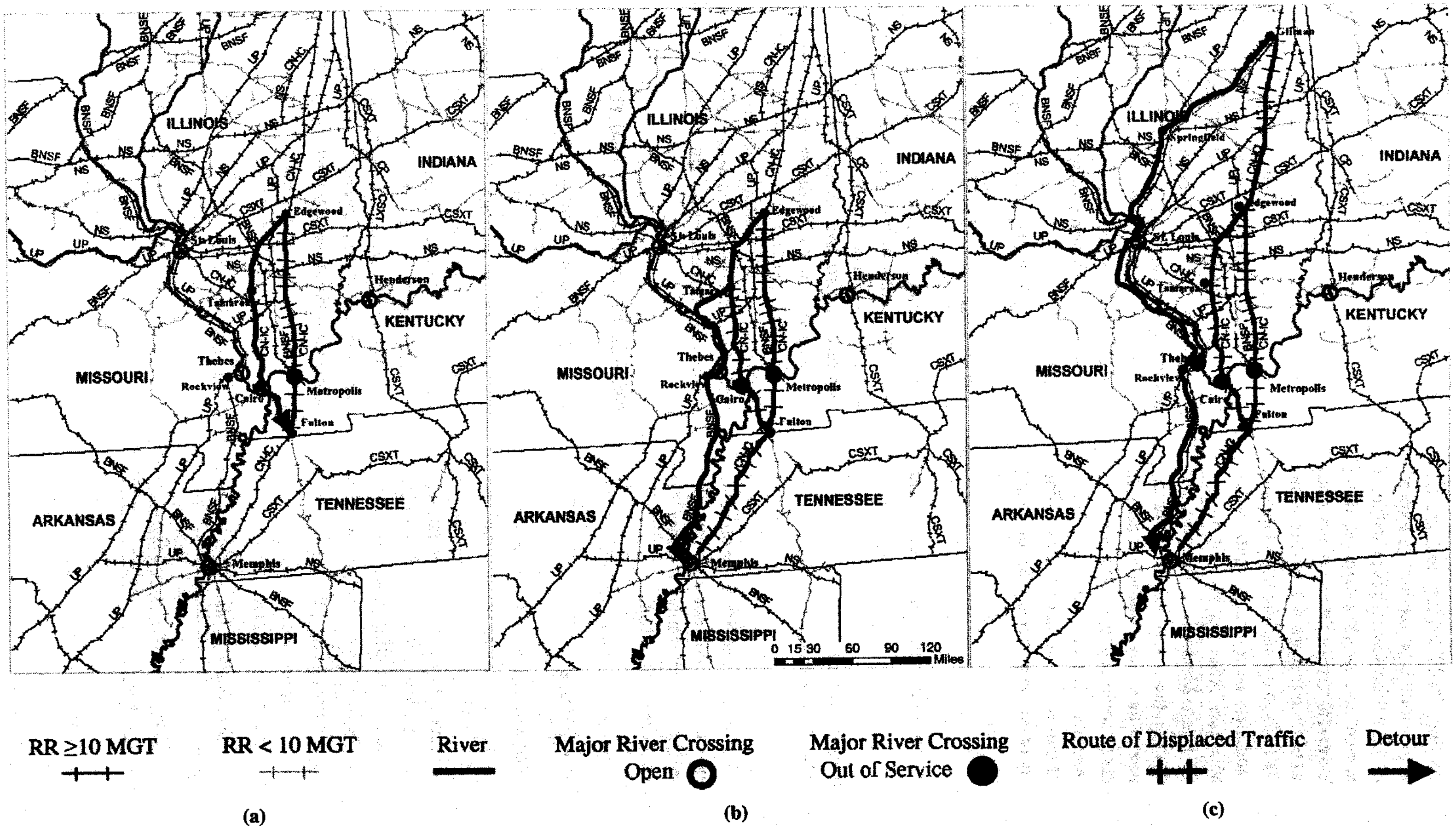

FIGURE 5 Possible detour scenarios for traffic on the CN-IC Railroad: *(a)* with Metropolis Bridge out of service; *(b)* with Metropolis and Cairo Bridges out; and *(c)* with Metropolis, Cairo, and Thebes Bridges out.

detour mileage over the UP and BNSF is 250 mi. 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 an extended period.

Because of 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 UP 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 5*c*). In this situation, the shortest route for the CN-IC is to use its line from Gilman, Illinois, to Springfield, Illinois, and then use trackage rights on UP from Springfield to St. Louis, Missouri. After reaching St. Louis, CN-IC traffic would use the BNSF line to Memphis, Tennessee, and then return to its mainline. In this case, the detour mileage over the BNSF is 278 mi. Here again, some of these lines might not be able to handle the rerouted traffic without some degree of upgrade.

The scenarios just described assume adequate capacity is available to handle the increase in traffic over the alternative lines. Some of the factors affecting the capacity of rail lines include the following (D. 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, and
- Level of service provided.

As mentioned, substantial excess capacity may not exist on some of the routes that would have to be used. A more thorough capacity analysis would need to be completed to determine whether the hosting railroad could manage the increase in traffic.

Example Bridge Retrofit Parameters

For the preceding example, the model was used with the input parameters appropriate to the three scenarios described to determine the EMV risk cost. Presumably, CN-IC's best option is to retrofit one of the two bridges on its mainlines to reduce the probability of damage given a major earthquake. This would allow CN-IC to keep traffic on its lines as much as possible, capacity permitting. It was assumed the CN-IC would choose to retrofit the Metropolis Bridge because: (*a*) it handles more traffic, (*b*) it is shorter, and (*c*) it is in a lower ground motion area (meaning a higher seismic resistance is gained by retrofitting). CN-IC provided data on the number of approach spans and main spans for the bridge at Metropolis. The following input parameter values were used to determine the EMV risk cost associated with retrofitting and not retrofitting this bridge:

- Bridge length = 5,660 ft
- Number of main spans = 7
- Number of approach spans = 39
- Annual traffic = 50 MGT
- Detour costs: variable cost = \$2.5/mi (*6*)
  - Fixed cost = \$62/train (*6*)
  - Lost revenue cost = \$0.024/mi (*6*)
- Repair cost for F_1 type failure = \$3,500/track ft (AREMA 9 and anonymous reviewers, unpublished data)
- Repair cost for F_2-type failure = \$700/track ft
- Cost to improve bearings
  - \$15,000/bearing for approach spans (M. Dooley, unpublished data)
  - \$65,000/bearing for main spans (W. G. Byers, unpublished data)
- Discount rate = 5% (*16*)

The estimated cost to retrofit the Metropolis bridge was \$4.16 million. The results of the three scenarios are presented in Table 2. If the risk cost exceeds the retrofit cost, retrofitting railway bridges may be cost-effective. Of the three scenarios, only the one requiring the longest detour (280 mi) combined with the longest repair time (1,500 days) resulted in a scenario in which retrofitting appeared to be cost-effective. To further understand the plausibility of combinations of circumstances in which retrofitting was rational, the model was used to conduct sensitivity analyses for several key parameters.

MODEL SENSITIVITY ANALYSIS

The three variables evaluated in the sensitivity analysis presented in Figure 6 were time to repair for an F_1-type failure, detour mileage, and annual traffic (MGT). The remaining input parameters were held constant, using data for the Metropolis, Illinois, bridge. The dashed horizontal line (*FC*) represents the estimated retrofit cost for the CN-IC Metropolis Bridge (\$4.16 million). The intersection point between the horizontal line (representing retrofit cost) and the sloping lines [representing detour lengths ranging from 50 to 450 mi, at two different traffic levels, 50 MGT (solid lines) and 100 MGT (dashed lines)] is the point where the risk cost exceeds the retrofit

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	537,895	888,535	350,639	4,160,000	-3,809,361
250	F_1=750 F_2=28	3,032,311	4,945,803	1,913,492	4,160,000	-2,246,508
280	F_1=1,500 F_2=90	6,781,426	11,144,647	4,363,221	4,160,000	203,221

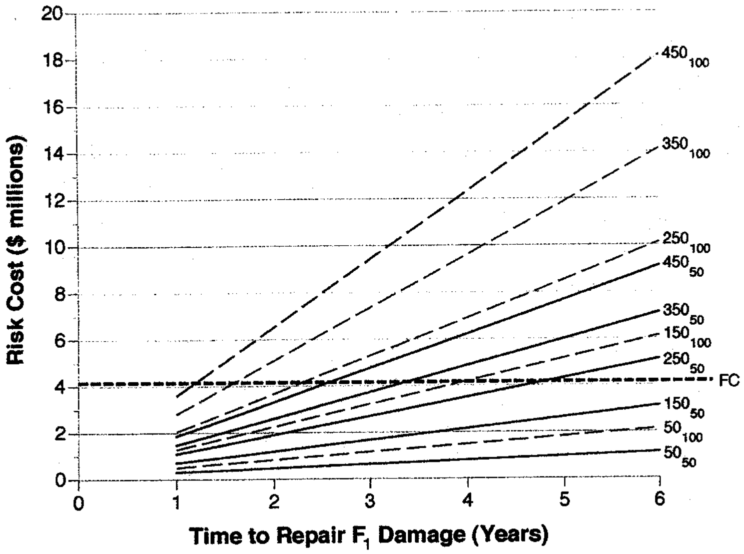

FIGURE 6 Sensitivity analysis for CN-IC Metropolis Bridge scenario: FC = estimated retrofit cost. Solid and dashed lines denote risk cost as a function of 50 and 100 annual MGT, respectively, for detour lengths ranging from 50 to 450 mi.

cost. For those combinations of time to repair, detour mileage, and traffic level when the risk cost is greater than the retrofit cost, retrofitting may be cost-effective.

Replacement or major repair of a bridge the size of the large Ohio and Mississippi crossings might take as long as 2 to 3 years (M. Johnson, unpublished data). However, arranging for funding and contracts would delay the onset of the work, thereby lengthening the interval. In the sensitivity analysis durations up to 6 years were considered (although the authors think this would be the extreme). The results indicate that when the detour length is 50 mi it would not be cost-effective to retrofit, irrespective of traffic, even at the maximum duration repair interval considered (Figure 6). However, as detour length and/or traffic increase, the cost-effectiveness of retrofitting becomes plausible for shorter bridge repair times. For lines with annual tonnage of 100 MGT, the cost-effectiveness of retrofitting a large bridge may be plausible when the requisite detour length is as short as 250 mi and the repair time is as little as 2 to 3 years.

Bearings are considered to be the most important railroad bridge element needing retrofit, and, in the sensitivity analysis, they were the principal cost element considered. However, if other options for retrofitting were also used (such as encasing piers, increasing footing sizes, etc.), the cost to retrofit would increase. This would increase the line, *FC* in Figure 6, thereby increasing the threshold criteria 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.

Some other parameters in the sensitivity analysis were also considered such as bridge replacement cost, discount rate, and higher transportation cost. Higher bridge replacement cost had only a small effect of increasing the threshold criteria for cost-effectiveness. If the discount rate increased, the NPV of the risk cost declined, also increasing the necessary threshold for retrofitting to be cost-effective. Conversely, higher transportation expense due to increased detour costs per ton or per train would increase the slope of lines denoting detour length. This would reduce the threshold criteria for the cost-effectiveness of retrofitting.

CONCLUSIONS

The Mid-America region is important to the U.S. rail network. Within the region about 2,107 route mi of trackage representing about 2.2% of the national total is exposed to potentially damaging PGAs (2% probability of experiencing >20% *g* in the next 50 years). Furthermore, there are a number of high-tonnage lines in the region including several with annual traffic levels >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 it was estimated that the total length for all bridges in areas potentially exposed to damaging PGA levels was about 306,800 ft (58 mi). Among these are eight bridges across the Ohio and Mississippi Rivers that carry about 245 million revenue tons of freight per year, accounting for 11.4% of the national total rail freight originated in the United States.

A model was developed to determine the cost-effectiveness of retrofitting railroad bridges for enhanced seismic resistance. The input parameters for the model include the following: 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 NPV 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 repair or replace shorter-span bridges relatively quickly. However, a sensitivity analysis based on data for the Ohio River bridge at Metropolis, Illinois, indicated that for large, strategically important bridges with a high concentration of traffic there are plausible scenarios for which retrofitting might be rational.