2. Loss Estimation Due to Seismic Risks to Highway Systems

Stuart D. Werner, M.EERI, Craig E. Taylor, M.EERI, and James E. Moore II

Earthquake losses due to highway damage depend not only on the response characteristics of the highway components, but also on the nature of the overall highway system (e.g., redundancies, capacities, traffic demands, etc.). This paper describes recent developments for addressing these issues by using seismic risk analysis (SRA) of the highway system. It outlines a new SRA procedure, describes its application to the Memphis, Tennessee highway system, and summarizes research being conducted to further develop the procedure.

INTRODUCTION

Past experience has shown that earthquake damage to highway components (e.g., bridges, roadways, tunnels, retaining walls, etc.) can severely disrupt traffic flows and, in turn, can impact the economy of the region as well as post-earthquake emergency response and reconstruction operations. Furthermore, the extent of these impacts will depend not only on the seismic response characteristics of the individual components, but also on the characteristics of the highway system that contains these components. System characteristics that will affect post-earthquake traffic flows include: (a) the highway system network configuration; (b) locations, redundancies, and traffic capacities and volumes of the system's links between key origins and destinations; and (c) component locations within these links (e.g., Basoz and Kiremidjian, 1996; Moore et al., 1995; Wakabayashi and Kameda, 1992).

From this, it is evident that earthquake damage to certain components (e.g., those along important and non-redundant links within the system) will have a greater impact on the system performance (e.g., post-earthquake traffic flows) than will other components. Unfortunately, such system issues are typically ignored when specifying seismic performance requirements and design/strengthening criteria for new and existing components; i.e., each component is usually treated as an individual entity only, without regard to how its damage may impact highway system performance. Furthermore, current criteria for prioritizing bridges for seismic retrofit represent the importance of the bridge as a traffic carrying entity only by using average

(SDW) Seismic Systems & Engineering Consultants, 8601 Skyline Blvd., Oakland CA 94611
(CET) National Hazards Management Inc., Torrance CA
(JEM) University of Southern California, Los Angeles CA

©Earthquake Spectra, Volume 13, No. 4, November 1997
daily traffic count, detour length, and route type as parameters in the prioritization process. Current practice does not account for the systemic effects associated with the loss of a given bridge, or for the combinatorial effects associated with the loss of other bridges in the highway system (Buckle, 1992; Moore et al., 1995). However, consideration of these systemic and combinatorial effects can provide a much more rational basis for establishing seismic retrofit priorities and seismic design and strengthening criteria for highway components.

In recognition of these issues, the National Center for Earthquake Engineering Research (NCEER) has included the development of improved system seismic risk analysis (SRA) procedures as part of its current six-year seismic research project entitled "Seismic Vulnerability of Existing Highway Construction." This paper describes the current status of the system SRA task being implemented under the NCEER project. It contains a description of the SRA procedure that has been developed, and provides a demonstration application of the procedure to the Memphis Tennessee highway system. Research being conducted to further develop the procedure is also summarized (see Werner et al., 1996).

**SEISMIC RISK ANALYSIS PROCEDURE**

**GENERAL DESCRIPTION**

This SRA procedure for a highway system that is being developed under this task is shown in Figure 1. It can be carried out for any number of designated scenario earthquakes and sets of input parameters. The various input parameter sets can differ from one another due to uncertainty effects. For each earthquake and input parameter set, the procedure uses geotechnical and structural engineering procedures, damage repair information, system traffic network analysis procedures, and socio-economic evaluations to estimate: (a) earthquake effects on system-wide traffic flows (e.g., travel times, paths, and distances); (b) economic impacts of highway system damage (e.g., repair costs and costs of travel time delays); and (c) post-earthquake traffic flows on individual roadways in the system (to facilitate emergency response planning). Key to this procedure is a modular GIS data base that contains the data and models needed to implement the system SRA.

The SRA results may either be deterministic or probabilistic. Probabilistic analysis is carried out by developing traffic flow and loss estimates for multiple scenario earthquakes and simulations, and then aggregating their results. A "simulation" is defined as a complete set of system SRA results for one particular set of input parameters and for a given analytical model. The models and input parameters for one simulation may differ from those for other simulations because of random and systematic uncertainties (Werner et al., 1996).

This SRA procedure has several desirable features. First, it has a GIS framework, to enhance data management, analysis efficiency, and display of analysis results. Second, the GIS data base is modular, to facilitate the incorporation of improved data and models as they are developed from future research efforts. Third, the procedure can develop aggregate SRA results that are either deterministic (consisting of a single simulation for one or a few scenario earthquakes) or probabilistic (consisting of multiple simulations and scenario earthquakes). This range of results facilitates the usefulness of system SRA for seismic retrofit planning, prioritizing, and criteria development for new or existing highway systems.
GIS DATA BASE

The GIS data base contains four modules that characterize the system, the seismic and geologic hazards, the component vulnerabilities, and the socio-economic impacts of highway system disruption due to earthquake damage. These modules serve as pre-processors to the four-step SRA procedure shown in Figure 1.

System Module

The system module contains the following information characterizing the highway system (as provided by transportation and urban planning specialists):

- **System Data**—including: (a) the system network topology, and component types and locations; (b) the number of lanes, observed traffic flows (if available), capacities, and congestion functions for each roadway link; (c) origin-destination (O-D) zone locations and demographics; and (d) any special characteristics of the system, such as particular roadways being critical for emergency response or national defense.

- **Traffic Management**—including in-place measures by local, county, or state transportation authorities for modifying the system to ease post-earthquake traffic flows (e.g., detour routes, modifications of roadways from two-way to one-way traffic, etc.)

- **Transportation Network Analysis Procedures**—for estimating pre- and post-earthquake traffic flows for each simulation and scenario earthquake. Associative memory procedures currently under development for this purpose are summarized later in this paper.

This SRA approach allows travel costs to be determined by the procedure, providing a realistic estimate of the way rational travelers are expected to use congested, overlapping paths. Post-earthquake changes in travel costs and link volumes resulting from damage to the transportation network are accounted for. These generalized costs and flows are computed as an equilibrium condition. Travelers compete for access to the network. Flows are computed such that the generalized cost of travel over any used path between any given O-D pair are equal, leaving no traveler with an incentive to change paths.

In addition, there are several elements in the data set can be treated as fixed prior to an earthquake, but would be expected to change following the event. This includes the magnitude of flows occurring between each combination of O-D pairs. Both the propensity to travel and the relative attractiveness of destinations will change following an earthquake, due to changes to the urban activity system and due to changes in equilibrium travel costs. Also, in a post-earthquake transportation network, not all trips are equally important. Traffic flows associated with emergency services should be treated with special priority. Unfortunately, introducing more than one kind of demand for access to the transportation network produces a nonlinear version of the multi-commodity flow problem, which is a difficult formulation to treat. Consequently, the systems module accepts fixed O-D requirements as a first-order

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1. To reflect the fact that time has value, we define the term “travel cost” to be a generalized quantity that combines out-of-pocket travel cost and time delay effects. Paths share links. Due to congestion, flows on one path influence the costs of other paths.
Figure 1. SRA procedure for highway transportation systems
approximation of post-earthquake demand, and travel demand remains aggregated in a single class of flows.

**Hazards Module**

The hazards module contains input data and models provided by geologists and geotechnical engineers to characterize system-wide ground motion, liquefaction, landslide, and surface fault rupture hazards. Input data include: (a) the scenario earthquake events to be considered for the SRA (including locations, activity rates, and magnitude potentials, and tectonic displacement data for the fault or seismic zone associated with each earthquake); (b) locations and topographic data for hills or slopes within the system that could be prone to landslide; and (c) local soil conditions throughout the system, as needed to estimate local geologic effects on ground shaking and the potential for liquefaction and landslide. Models contained in the hazards module will estimate: (d) the attenuation of bedrock motion with increasing distance from the earthquake source, for a range of earthquake magnitudes; (e) the effects of local soil conditions on the ground shaking; and (f) permanent ground displacements due to earthquake-induced landslide, liquefaction, and surface fault rupture. A deterministic representation of hazards models will employ mean values of these quantities. A probabilistic representation will use probability distributions to account for uncertainties in the seismologic, geologic, and soil input parameters and in the hazard evaluation models.

**Component Module**

The component module contains input data and models provided by structural and construction engineers to characterize each component in terms of a “loss model” and a “functionality model.” The loss model represents the component’s direct losses (i.e., repair costs), and the functionality model represents the component’s “traffic states” (i.e., whether the component will need to be partially or completely closed to traffic during the repair of the earthquake damage, the duration of these closures, and the allowable speed limits for traffic carried by the component during repair). Both models are a function of the level of ground shaking at the component’s site, as well as the level of permanent ground displacement due to liquefaction, landslide, or surface fault rupture. The models for each component are developed by evaluating: (a) its seismic response to each designated level of ground shaking and permanent ground displacement; (b) its “damage state,” i.e., the degree, type, and locations of any earthquake damage to the component; (c) how this damage will be repaired; and from this (d) the component’s traffic states at various times after the earthquake, reflecting the rate at which traffic along the component is restored as the repairs proceed.

After each component’s traffic states are obtained, they are incorporated into the highway system network model to obtain its overall “system state,” i.e., the ability of each link in the system to carry traffic at various times after the earthquake (in terms of number of open lanes, speed limits, etc.). These system states are time-dependent to reflect the above-indicated time dependence of the various component traffic states. In addition, the system state will reflect the effect of each component’s damage state on adjacent, underlying, and overlying roadway links. This, of course, will also be a function of the location of the component within the overall system, as well as the system network characteristics.
A deterministic representation of loss and functionality models will employ mean values of the component repair costs and traffic states. A probabilistic representation will use probability distributions to account for uncertainties in the evaluation of the component seismic response, and in the estimation of the resulting repair costs and traffic states.

Socio-Economic Module

The socio-economic module contains models and data for evaluating broader social and economic impacts of earthquake-induced traffic flow disruptions. These impacts can include indirect dollar losses (e.g., to commuters and businesses), effects on emergency response (e.g., reduced access to medical, police, fire-fighting, airport, government centers, etc.), and societal effects (e.g., reduced access to residential areas, shopping areas, etc.). This module is developed by transportation specialists, urban planners, and economists.

ANALYSIS PROCEDURE

Step 1: Initialization of Analysis

The initialization of the SRA (Step 1) contains two parts. First, regional earthquake source models are used to define an ensemble of scenario earthquakes. Each earthquake is most commonly defined in terms of its magnitude, location, and frequency of occurrence. Uncertainties in defining the values of the various earthquake input parameters may also be modeled at this stage. The second part of Step 1 establishes the total number of simulations for each scenario earthquake, as further described in Werner et al. (1996).

Step 2: Development of \( n_i \)th Simulation for \( i \)th Scenario Earthquake

In the next step of the SRA procedure, the following evaluations are carried out to develop the \( n_i \)th simulation for the \( i \)th scenario earthquake \((i=1,2,...,I)\), where \( n_i = 1, 2, \ldots, N_i \); and \( N_i \) is the total number of simulations for the \( i \)th earthquake:

**Hazard Evaluation.** First, the data and models contained in the hazards module are used to estimate the earthquake ground motions and geologic hazards throughout the system.\(^2\)

**Direct Loss and System State Evaluation.** Once the hazards are estimated, the data and models from the component module are used to evaluate direct losses and system states (defined at various times after the earthquake).\(^2\)

**Traffic Flow Evaluation.** The system data and models from the system module are applied to the pre-earthquake (undamaged) system and to the above post-earthquake system states to assess earthquake effects on system-wide travel times, travel distances, and travel paths, as well as traffic flows along key roadways critical to emergency response.

**Socio-Economic Impact Evaluation.** Once the earthquake effects on traffic flows within

\(^2\) If probabilistic evaluations are being carried out, the seismic hazard probability distributions are sampled to obtain the hazards at each component site for each simulation. Then, the probability distributions for the component loss and functionality models are sampled for the appropriate hazard levels, to obtain the corresponding repair costs and traffic states for each component.
the system are evaluated, the data and models from the socio-economic module are used to evaluate impacts of the impeded traffic flows in terms of: (a) indirect dollar losses; (b) reduced access to and from emergency response centers and (c) various societal impacts, including land use changes associated with changes in the value of sites.

**Step 3: Incrementation of Simulations and Scenario Earthquakes**

Under Step 3, the evaluations from Step 2 are repeated to develop multiple simulations for multiple scenario earthquakes (if the SRA is to be probabilistic).

**Step 4: Aggregate System Analysis Results**

This final step in the SRA process is carried out after the system analyses for all simulations and scenario earthquakes have been completed. In this step, the results from all simulations and earthquakes are aggregated and displayed. Depending on user needs, these aggregations could focus on the seismic risks associated with the total system or with individual components. Furthermore, the system or component results could be provided: (a) for individual simulations, which is termed a seismic vulnerability analysis, and/or (b) for the broader (probabilistic) range of simulations, leading either to loss statistics (e.g., average annualized loss) or to loss distributions that show the severity of earthquake-induced system losses for different probability levels. For research purposes, the impacts of incorporating uncertainties into the SRA will be of considerable interest. For other purposes, such as the planning of seismic strengthening programs for existing highway systems, outputs can be adapted and/or simplified to meet the particular requirements of each user audience.

**DEMONSTRATION SEISMIC RISK ANALYSIS**

**OBJECTIVE AND SCOPE**

The SRA procedure has been used to carry out a demonstration analysis of the Memphis, Tennessee highway system (Figure 2). The analysis uses current data and models to carry out a deterministic SRA for four scenario earthquakes. The objectives of the analysis are to: (a) demonstrate the application of SRA and the types of results that can be obtained; (b) illustrate the level of development of the current data and models for implementing system SRA; and (c) provide a basis for identifying and prioritizing research needs for improving the SRA procedure. Because of limitations in many of the current data and models, the results of this SRA should be regarded only as very preliminary. As improvements are developed through future research, the reliability of the SRA results will increase substantially. Current research to improve the SRA procedure is summarized later in this paper.

**SYSTEM**

The city of Memphis is located in southwestern Tennessee, just east of the Mississippi

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3. The loss can be defined in several ways, such as direct repair cost, travel time delays due to earthquake damage (between certain key origin-destination zones or aggregated over all zones), indirect losses due to travel time delays, or other adverse consequences.
Figure 2. Memphis area highway system
River and near the New Madrid seismic zone. The city's highway and roadway system consists of: (a) a beltway of interstate highways that surrounds the city; (b) two major crossings of the Mississippi River (at Interstate Highways 40 and 55); and (c) major highways and roadways both within and just beyond the beltway that extends to transportation, residential, and commercial centers throughout the greater Memphis area (Figure 2). The system contains a total of 286 bridges and 314 O-D zones.

The network is modeled at the level of detail representative of transportation planning models maintained by Metropolitan Planning Organizations (MPOs). The Memphis MPO's MINUTP model of the network includes arcs corresponding to high design physical links such as freeways, state highways, and major arterials. The level of network detail should be sufficient to account for facilities subject to earthquake damage, permit designation of small travel analysis zones in dense areas, and to account for redundant paths. The network must be sufficiently aggregate to avoid infeasible computational burden. The level of detail associated with the network representation used in the SRA exercise represents the practical limit of the Memphis MPO's transportation modeling capabilities. More detailed representations are possible. As described later in this paper, we are constructing new rapid network equilibrium estimation procedures that will permit both greater detail and more scenarios, but the SRA procedure is designed to use transportation planning data available at the level expected to be available in practice.

It is noted that the O-D zone trip tables used in this analysis address interzonal travel times only. Intrazonal times are not included because intrazonal travel is not represented in MPO-furnished trip tables. Intrazonal trips are frequent, but account for a relatively small proportion of the total travel time. Interzonal networks are presumed to be robust enough to accommodate these short trips without significant changes.

ASSUMPTIONS

Scenario Earthquakes

This SRA was carried out for four scenario earthquake events that encompass a range of moment magnitudes and locations (Figure 3a). The events are: (a) Earthquake A, which has a moment magnitude $M_w = 7.5$ (corresponding to the largest earthquake in the 1811-1812 sequence) and is located at the southern end of the New Madrid seismic zone (Zone A in Figure 3a); (b) Earthquake B, which has a moment magnitude $M_w = 6.5$ and is located near the center of Zone A; (c) Earthquake C, which has a moment magnitude $M_w = 6.0$ and is located in Zone B to the west of Zone A; and (d) Earthquake D, which has a moment magnitude $M_w = 5.5$ and is located in Zone B east of Zone A. The distances from the epicenters of these earthquakes to the Memphis highway system range from 35-50 km (for Earthquake D) to 110-125 km (for Earthquake C). This paper provides results for Earthquake D only. Werner and Taylor (1995) provides results for the other earthquake events.

System Module

The only system components considered in this demonstration SRA are bridges and roadways. The system does not contain any tunnels, and other system components (e.g., retaining walls, etc.) have not been considered. The system's network configuration was
Figure 3. Scenario earthquakes and local geology
obtained from a GIS database provided by the University of Memphis. The traffic flow and volume data, roadway traffic capacities, and O-D zones within the system were provided by the Memphis and Shelby County Office of Planning and Development (OPD). The traffic flow data were from their 1988 traffic forecasting model.

Our analysis of the impacts of each scenario earthquake on traffic flows within the Memphis area highway/roadway system was carried out using the MINUTP traffic forecasting software (Comsis, 1994). This software was selected because it is currently used at the Memphis-Shelby County OPD, and all regional traffic data were available in the input format for this software. MINUTP is one of several standard PC-based software packages that are available for transportation system analysis and are based on the Urban Transportation Planning System (UTPS) developed over two decades ago by the U.S. Department of Transportation (Ferguson et al., 1992). As discussed in Werner et al. (1996), the UTPS has certain deficiencies pertaining to its use in highway system SRA. Furthermore, the version of MINUTP that was available at the time of our SRA was not GIS-compatible, and this greatly increased the effort required to carry out our system analyses. For these reasons, current research under the NCEER Highway Project is developing an improved transportation network analysis procedure which is summarized later in this paper.

Hazard Module

The only seismic and geologic hazard that has been considered in this SRA is ground shaking. Potential hazards from liquefaction, landslide, and associated ground movement have not been included because of a lack of suitable data for carrying out such evaluations over a spatially dispersed region and for a range of scenario earthquake events. The ground shaking hazard was represented in terms of peak ground acceleration (PGA). It was estimated in two steps. First, bedrock accelerations at each bridge site due to each scenario earthquake were estimated using the attenuation equation developed by Hwang and Huo (1994). Then, effects of local soil conditions at each bridge site were represented by multiplying the bedrock accelerations by local geology factors developed by Martin and Dobry (1994) for various site categories and bedrock acceleration levels. This was based on the local geology mapping of the area carried out at the University of Memphis (Figure 3b), and is contained in our GIS data base for this demonstration SRA (Hwang and Lin, 1993). Figure 4 shows the resulting bedrock and peak ground accelerations for Earthquake D.

Component Module—Loss Model

In this demonstration SRA, loss models previously developed under the ATC-25 project for conventional highway bridges were used to estimate direct losses for each bridge in the system due to each earthquake (ATC, 1991). In these models, the direct losses depend only on whether the bridge has simple spans or is continuous/monolithic; i.e., other bridge structural attributes that could impact seismic performance are not considered. Improved bridge models that consider these attributes are being developed as a high priority research objective under the NCEER Highway Project. These are summarized later in this paper.

Component Module—Functionality Model

Because of a lack of suitably-compiled data describing post-earthquake traffic flows, repair procedures, and repair times for a given type and degree of bridge damage, only a very
Figure 4. Peak acceleration (g) due to Earthquake "D." *In color* see plates following p. 738.
simple and approximate functionality model could be used for this demonstration SRA. This model was based on prior observations of the seismic performance and post-earthquake repair/reconstruction of older bridges in California during the Loma Prieta and Northridge Earthquakes (Werner and Taylor, 1995). It represents the component traffic states as the number of lanes open at discrete times after an earthquake, as a function of PGA and the original number of lanes along the bridge. The models simulate bridge lane closures due to structural damage only, and do not consider other possible causes of closures after an earthquake (e.g., approach fill settlement).

Two different models were developed in accordance with the ATC-25 conventional highway bridge designations—one for bridges with simple spans and one for continuous/monolithic bridges. Reductions in traffic speeds were not considered at this time. In addition, to illustrate effects of the time dependence of the repair process on the post-earthquake system performance, functionality models were developed for two discrete times—three days and six months after the earthquake. The first was selected to represent circumstances soon after the earthquake, before any repairs have been made but after undamaged bridges had been reopened and lane closures to accommodate post-earthquake repair had been established. The second time was chosen to represent circumstances when some time has elapsed following the earthquake, when some bridge repair had been made and at least some lanes on damaged bridges had been reopened to traffic.

Socio-Economic Module

Studies of economic impacts of earthquake-induced highway system damage have shown that indirect dollar losses due to such damage can far exceed the direct losses for repair of the damage (e.g., Gordon and Richardson, 1995). However, systematic procedures for predicting such impacts for future earthquakes are not yet well developed, and only simplified and approximate procedures are currently available for this purpose.

One such procedure is described in the Caltrans Policy and Procedure Circular P78-5 Revised. This procedure, which has been used to estimate economic impacts of damage to the Santa Monica freeway during the 1994 Northridge Earthquake (BAA, 1994), has also been used to in this demonstration SRA to estimate economic impacts of highway system damage. The costs estimated by this procedure are only due to deterioration in commute time, and do not consider the numerous other possible economic impacts of earthquake damage to a highway system. These cost estimates are based on vehicle-hours of delay (as obtained from the MINUTP system analyses in this demonstration SRA), corresponding person-hours of delay (based on an assumed average vehicle occupancy rate of 1.4 persons/vehicle), truck-hours of delay (assuming a certain percentage of the total number of vehicles are trucks), and excess fuel costs due to travel time delays (BAA, 1994). A more general theoretical framework for evaluating economic impacts of transportation network damage is given by Gordon, Moore, Richardson, and Shinozuka (1997), although this research model is still under development.

The estimation of economic impacts was based on system vehicle mix data for Shelby County that was provided by the Memphis and Shelby County OPD. These data indicate that about 70 percent of the traffic in the Memphis area is due to non-truck (i.e., primarily automobile) vehicles, and the remaining 30 percent is truck traffic.
RESULTS

Direct Loss Estimates for Scenario Earthquake D

In accordance with the ATC-25 model used in this demonstration SRA, direct losses due to damage to the system's bridges are represented as a damage ratio, DMG (%), which is defined as the ratio of the repair cost for each bridge to its total replacement cost.

The damage ratios for each of the 286 bridges in the Memphis area highway/roadway system due to each scenario earthquake are tabulated in Werner and Taylor (1995). We computed average damage ratios (averaged over all of the 286 bridges) for each earthquake to approximately compare the relative effects of each earthquake on the direct losses throughout the system. For Earthquake D, this average damage ratio was 37.4%. As discussed in Werner and Taylor (1995), this damage ratio turned out to be much larger than that computed for Earthquake C (which had relatively minor effects on the system), and was slightly larger than the average damage ratio computed for Earthquake B. Earthquake A, which was by far the most severe of the four scenario earthquakes considered, resulted in damage ratios that were substantially larger than those due to Earthquake D.

Post-Earthquake Travel Times and Distances for Earthquake D

System State Results. Figure 5 shows the pre-earthquake system state and post-earthquake system states at three days and six months after Earthquake D. This figure indicates that, although Earthquake D has only a moderate magnitude (\(M_w = 5.5\)), its proximity to the northern segment of the Memphis highway system causes extensive roadway closures in that segment, with lesser impacts on other segments of the system.

Table 1. Effects of Earthquake D on total system travel times and distances

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>PRE-EARTHQUAKE VALUE</th>
<th>TIME AFTER EARTHQUAKE = 3 DAYS</th>
<th>TIME AFTER EARTHQUAKE = 6 MONTHS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Percent Increase over Pre-EQ</td>
<td>Value</td>
</tr>
<tr>
<td>Total vehicle hours traveled over 24-hour period (incl. congestion)</td>
<td>(3.73 \times 10^5)</td>
<td>(4.99 \times 10^5)</td>
<td>33.8</td>
</tr>
<tr>
<td>Total travel distance (mi) over 24-hour period</td>
<td>(15.5 \times 10^6)</td>
<td>(15.6 \times 10^6)</td>
<td>small</td>
</tr>
</tbody>
</table>

Total System-Wide Travel Times. Table 1 contains the total pre- and post-earthquake travel times and distances for the Memphis highway system. This table shows that the modified system states due to Earthquake D result in a total system-wide travel time three
a) Pre-Earthquake

b) Post-Earthquake

Figure 5. System states
days after the earthquake that is nearly 34 percent longer than the pre-earthquake values. At six months after the earthquake, the bridge repairs within that time have reduced the total travel time; however it is still nearly 20 percent longer than the pre-earthquake value. It is noted that accounting for changes in post-earthquake travel demands between O-D pairs relative to pre-earthquake demands would lead to total travel times that are lower than those shown in Table 1. This is because post-earthquake travel demands would involve trips that are shorter and/or less frequent than those associated with pre-earthquake demands; i.e., after an earthquake, there will be an adjustment in demand for destinations in addition to changes in routes. Since travel times have increased, some degree of adjustment is likely. This is an important extension, and is a focus of ongoing research.

**Total System-Wide Travel Distances.** Table 1 shows that the total system-wide travel distances at three days and six months after the occurrence of Earthquake D are not sensitive to the modified system states. This is to be expected, since earthquake damage will result in a

<table>
<thead>
<tr>
<th>Origin-Destination Zone (see Figure 2b for zone locations)</th>
<th>Pre-Earthquake Travel Time (Hours)</th>
<th>3 Days After Earthquake</th>
<th>6 Months After Earthquake</th>
<th>Travel Time</th>
<th>Percent Increase over Pre-Earthquake Time</th>
<th>Travel Time</th>
<th>Percent Increase over Pre-Earthquake Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government Center (downtown Memphis)</td>
<td>7 128</td>
<td>143 11.7</td>
<td>133 3.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Medical Center</td>
<td>8 122</td>
<td>141 15.6</td>
<td>130 6.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>25 122</td>
<td>136 11.5</td>
<td>127 4.1</td>
<td>121 6.1</td>
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<td></td>
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<tr>
<td>26 114</td>
<td>129 13.2</td>
<td>121 6.1</td>
<td>121 6.1</td>
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<td>27 114</td>
<td>129 13.2</td>
<td>121 6.1</td>
<td>121 6.1</td>
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<td>129 12.2</td>
<td>121 5.2</td>
<td>124 4.2</td>
<td></td>
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<td>122 2.5</td>
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<tr>
<td>University of Memphis</td>
<td>111 119</td>
<td>131 10.1</td>
<td>122 2.5</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>President’s Island (Port)</td>
<td>151 138</td>
<td>153 10.9</td>
<td>144 4.3</td>
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<td>Memphis Airport</td>
<td>188 136</td>
<td>150 10.3</td>
<td>142 4.4</td>
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<td>Federal Express</td>
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<td>145 11.5</td>
<td>136 4.6</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mall of Memphis</td>
<td>201 127</td>
<td>145 14.2</td>
<td>133 4.7</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Hickory Hall</td>
<td>213 171</td>
<td>185 8.2</td>
<td>177 3.5</td>
<td></td>
<td></td>
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<tr>
<td>Poplar-Ridgeway</td>
<td>230 130</td>
<td>148 13.8</td>
<td>136 4.6</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Germantown</td>
<td>231 130</td>
<td>147 13.1</td>
<td>136 4.6</td>
<td></td>
<td></td>
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<tr>
<td>Shelby Farms</td>
<td>236 141</td>
<td>157 11.3</td>
<td>147 4.3</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Bartlett</td>
<td>241 176</td>
<td>187 6.3</td>
<td>181 2.8</td>
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<tr>
<td>Covington Pike</td>
<td>249 169</td>
<td>176 4.1</td>
<td>174 3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>252 127</td>
<td>211 66.1</td>
<td>152 19.7</td>
<td>155 4.7</td>
<td></td>
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<td></td>
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<tr>
<td>264 148</td>
<td>199 34.5</td>
<td>155 4.7</td>
<td>151 10.2</td>
<td></td>
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<tr>
<td>274 137</td>
<td>181 32.1</td>
<td>151 10.2</td>
<td>151 10.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>TOTALS</strong></td>
<td>2813 3255</td>
<td>15.7</td>
<td>2963 5.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
lengthening of some trip distances and a shortening of other trip distances (i.e., some drivers will be forced to use slower but more direct routes because of roadway closures). The loss of one physical path due to earthquake damage may not impose much of a distance penalty, but may impose considerable time penalties due to congestion and increases in travel volumes.

**O-D Zone Travel Times.** Table 2 shows that, at three days after Earthquake D, the travel times between the O-D zones listed in the table are, on the average, nearly 16 percent larger than those for the pre-earthquake system. The travel time increases are largest for northernmost of the highlighted zones, which are at Shelby Farms (Zones 249 and 252), Bartlett (Zone 264), and the Covington Pike (Zone 274). This is because, again, this section of the Memphis area highway and roadway system most severely damaged by Earthquake D. At 6 months after Earthquake D, travel times to and from these zones have been reduced substantially, and now exceed pre-earthquake values by only 5.3 percent.

**O-D Zone Travel Distances.** The travel distances to and from the O-D zones listed in Table 2 are not sensitive to damage from Earthquake D (Werner and Taylor, 1995).

**Economic Impacts.** Estimates of economic impacts of highway system damage due to Earthquake D are shown in Table 3, and are based on total system-wide travel time delays per 24-hour day of 126,000 vehicle-hours and 73,000 vehicle-hours at three days and six months after the earthquake respectively (see Table 1). Given these figures, and using truck vs. non-truck traffic breakdowns for the Memphis area, the Caltrans cost estimation procedure leads to a total cost per day of the earthquake-induced time delays of $1.6 million at three days after the earthquake, and $930 thousand at six months after the earthquake. Taking this six month value of $930 thousand per day as average daily time-delay cost for the year, the total cost of the system-wide time delays over a period of one year following Earthquake D is computed to be $340 million, as shown in Table 3.

**Table 3. Economic impacts of travel time delays due to scenario Earthquake D**

<table>
<thead>
<tr>
<th>Time After Earthquake</th>
<th>Time Delay (Vehicle-Hours/24-Hour Day)</th>
<th>Cost/Day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Non-Trucks</td>
</tr>
<tr>
<td>3 Days</td>
<td>126,00</td>
<td>88,200</td>
</tr>
<tr>
<td>6 Months</td>
<td>73,000</td>
<td>51,100</td>
</tr>
</tbody>
</table>

*Estimated Cost for One-Year Time Period:*

Assume Average Time-Delay/24-Hour Day = 73,000 Hours

**Estimated Cost** = ($9.3 \times 10^5) \times 365 \text{ Days} = $340 \times 10^6

**CURRENT RESEARCH**

The demonstration SRA identifies the improvement of bridge vulnerability models and transportation network analysis procedures as the highest priority research needs. Research currently being conducted to address these needs is summarized below. Other important
research needs pertain to vulnerability modeling for (non-bridge) highway components, further development of the hazards and socio-economic modules, and incorporation of uncertainty effects. These are discussed further in Werner et al. (1996).

BRIDGE VULNERABILITY MODELING

Improved bridge vulnerability models are being developed as a joint effort of several investigators from the NCEER Highway Project. The first step in this process will consist of an evaluation of the applicability of several current seismic analysis procedures to the estimation of bridge damage states, by applying each procedure to representative bridge configurations. This will not only involve an assessment of each procedure’s ability to develop plausible damage state predictions, but also the cost and time requirements for applying the procedure to the many bridge types that comprise a given highway system.

From this, a preferred procedure will be identified and used to estimate damage states for various types of typical bridges in the Memphis highway system, and for various levels of ground shaking. These damage state results will then be provided to several experts in bridge repair and construction, who will independently develop best estimates of procedures, costs, and time requirements to repair each damage state, as well as the impact of the damage on traffic along the component and its adjacent roadways. A workshop involving the bridge repair experts will be held to discuss and review these results, after which the results will be synthesized and used to develop improved traffic state models for the Memphis area bridges.

TRANSPORTATION NETWORK ANALYSIS PROCEDURES

Incorporation of an improved transportation network analysis procedure is a high priority research need because of the noted deficiencies in the UTPS with respect to its use in highway system SRA. An improved procedure should: (a) represent the latest technology; (b) be adaptable to GIS; (c) be applicable to a highway system with substantial roadway closures due to earthquake damage; (d) be cost-effective to implement; and (e) use available transportation system input data.

A procedure developed by Moore et al. (1995) was judged to best incorporate the above attributes. This procedure provides inexpensive and dependable estimates of flows and commuting times in congested networks in response to changes in link configuration due to earthquake damage. It is based on associative memory (AM) approaches derived from the artificial intelligence field to predict the changes in highway system flows. The improved procedure provides good approximate solutions to constrained optimization problems representing the economic determinants of these flows. An AM matrix is used to map given sets of system network configurations (stimuli) into corresponding traffic flows (responses).

During the past year of the NCEER Highway Project, the procedure was thoroughly documented and applied to several test cases (Kim et al., 1997). Further development of the procedure and its incorporation into an integrated software package for SRA of highway systems is planned for the next year of the NCEER Highway Project.
CONCLUDING COMMENTS

This paper has described a new SRA procedure for highway systems. A successful demonstration application of the procedure to the Memphis highway system has provided preliminary results that show the type of information that can be obtained using SRA. As further research and data compilation is carried out, the reliability of the system performance results obtained using SRA should increase dramatically. We anticipate that significant progress along these lines will be achieved over the next years of the NCEER Highway Project, and that a planned re-analysis of the Memphis highway system using the improvements developed from this research should substantially improve the SRA results.

SRA can enhance the prioritization, planning, and implementation of seismic risk reduction for highway systems. Its principal benefit is its ability to directly represent seismic performance of highway systems—in terms of post-earthquake traffic flows—and to represent systemic effects of damage to various highway components. This information will provide an improved basis for making decisions regarding the establishment of priorities for seismic strengthening of highway components, the establishment of component seismic performance and design criteria, the planning of emergency response and other seismic risk reduction measures, and the justification of funding for these measures.

ACKNOWLEDGEMENTS

This research is being funded by the National Center for Earthquake Engineering Research (NCEER) under their Highway Project. This financial support is gratefully acknowledged. The authors also wish to acknowledge the following individuals: (a) Dr. Ian Buckle and Mr. Ian Friedland of NCEER and Prof. Masanobu Shinozuka of the University of Southern California, for their encouragement and helpful suggestions; (b) Prof. Howard Hwang of the University of Memphis and Mr. John Jernigan of Ellers, Oakley, Chester, & Rike in Memphis TN, for their generosity in sharing GIS and bridge data for the Memphis area with us; (c) Messrs. Clark Odor, Abdul Razak, and Esther Anderson of the Memphis and Shelby County OPD, for providing traffic data and assistance with the MINUTP traffic flow analyses; (d) Mr. Edward Wasserman and his staff at the Tennessee Department of Transportation in Nashville, Tennessee, for providing us with bridge data, drawings, and reports; and (e) Mr. Jon Walton, for his work on the GIS aspects of this project.

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