Estimation of Earthquake Loss Due to Bridge Damage in the St. Louis Metropolitan Area. II: Indirect Losses

David Lee Enke
Missouri University of Science and Technology, enke@mst.edu

Chakkaphan Tirasirichai

Ronaldo Luna
Missouri University of Science and Technology, rluna@mst.edu

Estimation of Earthquake Loss due to Bridge Damage in the St. Louis Metropolitan Area: Part II - Indirect Loss

David L. Enke[1], Chakkaphan Tirasirichai[2], and Ronaldo Luna[3]

ABSTRACT

An approach to estimate the indirect economic loss due to damaged bridges within the highway system from an earthquake event is presented. The indirect cost considered refers to the increased highway transportation cost only. The study zone covers the St. Louis metropolitan area and its surrounding suburban regions. An earthquake scenario centered in St. Louis, Missouri with a magnitude 7.0 is used. The direct earthquake loss was primarily damage to bridges, which causes an increase in travel time and distance within the transportation network. This information is then used as input for the indirect loss model. The indirect loss is examined from an economic perspective. The results reveal that the indirect loss is significant when compared to the direct loss resulting from bridge damage. From the study results, a transportation network planner can prepare an appropriate preventive action plan (such as choosing alternative routes for potential damaged links, as well as reinforcing possible high damage bridges) to reduce the potential losses before the earthquake occurs.

[1] Associate Professor, Department of Engineering Management and Systems Engineering, University of Missouri, Rolla, MO. Email: enke@umr.edu

[2] Graduate Research Assistant, Department of Engineering Management and Systems Engineering, University of Missouri, Rolla, MO. Email: cttz4@umr.edu

[3] Associate Professor, Department of Civil, Architectural and Environmental Engineering, University of Missouri, Rolla, MO. Email: rluna@umr.edu

INTRODUCTION

When an earthquake occurs, it produces serious consequences, such as infrastructure damage, socio-economic impact, or even loss of life. One part of these consequences can be noticeably observed as damage to physical facilities, such as damage to buildings and residences, collapse of bridges, indoor property loss, and breakdown of utility systems. One part of the costs associated with infrastructure damage is the loss of associated asset value. This loss can be measured by the repair or replacement costs resulting from damage and can often be labeled as the direct economic loss (Brookshire et al. 1997; An et al. 2004; CGER 1999; Lindell and Prater 2003). In addition, there are other costs associated with these consequences as well, called indirect economic losses. These losses represent the consequences of earthquake destruction, such as temporary unemployment and business interruption. Damage in the facilities of one industry sector can also have an effect on other related sectors. For instance, the lower capacity of the transportation network will result in lower production capacity for each industry sector due to reduced material deliveries or fewer employees having access to the company. In addition to losses that may result from the earthquake, some economic gains may also result. It is not uncommon for the damage to the infrastructure to create increased activity in the construction sector (FEMA 2001; CGER 1999; Brookshire et al. 1997).

The Importance of Loss Estimation

Each earthquake can cause extensive economic losses. Table 1 provides approximate values for the losses from multiple earthquake scenarios provided from various researchers and organizations. In addition to these loss figures, the Federal Emergency Management Agency (FEMA) estimates an anticipated annualized earthquake loss of $17 million (FEMA 2001).

Based on the figures of losses from earlier studies, one can easily be convinced that it is valuable to know in advance estimates of the potential loss figures in order to be better prepared for an unexpected event.

An earthquake is an inevitable situation for locations near a seismically active geologic setting. However, the effect from the disaster can be dramatically reduced by appropriate preventive policies, such as land use planning and the reinforcement of structures. Thus, it is important for policy makers to know estimates of potential loss figures in advance. This will allow future risk evaluation to be conducted by comparing earthquake hazard prevention investment with approximated earthquake hazards, resulting in the design and implementation of mitigation strategies. In addition to the interest of policy makers in the loss figure, the insurance industry is also interested in the approximate loss figures, so they can design and introduce products (e.g., insurance plans and policies) into the market. Furthermore, individuals can also benefit from knowing the possible/potential loss information in order to help choose which insurance option will offer the best protection and value (CGER 1999; Boisvert 1992; Junqi et al. 2004).

An example of a well-designed loss reduction mitigation plan is presented by Rose and Lim (1997). This study for the Northridge Earthquake found that the proper reallocation of electricity resources across sectors and sub-regions in the aftermath of the earthquake could have reduced the loss from electricity utility disruption by more than 70% if the electricity had been rerouted to those sectors contributing most to gross regional product.

Most studies tend to focus on the direct loss, which is easier to notice. However, the indirect loss happens to be a significant portion of the total loss that results from an earthquake. For example, the Veneziano et al. (2002) study showed that for the hypothetical Memphis

earthquake and its impact on transportation capacity, the indirect losses have a significant dollar figure compared to the direct loss, being about 30% of the direct losses. In order to consider indirect losses, researchers have to extend their concern beyond the physical damage and also consider the consequence of these damages.

STUDY FRAMEWORK

Indirect Loss Definition and Scope of Study

It is obvious that an earthquake can cause significant losses beyond physical damage. Unfortunately, it is practically impossible to capture every indirect loss resulting from an earthquake by a single economic model since there is too much information to consider from a wide variety of sectors in order to make a reliable estimate (CGER 1999). Even if the scope of the concerned loss is identified, it is still a complicated process to make the indirect loss estimate. For example, to observe the losses from the damaged utility lifelines, Boisvert (1992) recommended considering the effects from each lifeline failure separately and then combining the losses calculated from damage to each to determine the total losses. Unfortunately, combining these losses will cause a double counting problem. Furthermore, the accuracy of the estimates is also difficult to assess in terms of how to aggregate across the different lifelines. In order to avoid the overestimation issue, Boisvert alternatively suggested representing the total indirect loss from lifeline failure by the largest loss from a single damaged lifeline. To achieve this, the definition or scope of the indirect loss, which will be captured by a designed economic model, must be carefully defined.

The primary consideration of this study is to capture the loss resulting from the damaged bridges in the highway network. In addition to other major concerns, which include time limitations, the availability of information, and the connection with the direct loss estimate study (Luna et al. 2007), the indirect economic loss of this study is limited in scope and subsequently labeled as the "Partial Indirect Economic Loss: The Impact on Highways for the Traveling Public". The definition of this partial indirect loss is defined as the expected financial loss that occurs from increased transportation costs in the highway network. These are the costs resulting from the increased time and distance used for transportation as a result of damaged bridges lowering the capacity of the highway network. These costs play an important part when the cost benefit analysis of the road project is conducted.

Framework Diagram

As discussed earlier, the framework of this study is specifically designed and based on the partial indirect loss definition and scope presented in Figure 1.

The highway damage evaluated in the direct loss estimation (Luna et al. 2007) is the bridge damage. The partial indirect loss estimation framework is designed as an integrated framework consisting of three connected parts: the HAZUS software, the transportation network model, and the economic module. An earthquake scenario is used to investigate the damaged bridges utilizing the HAZUS-MH (Multi-Hazard HAZUS) software. The damaged bridges are identified using this FEMA developed software (which estimates the direct loss associated with these damaged bridges). Then, based on that bridge damage information, changes in the transportation network are made to calculate the changes in travel time and distance using a transportation network model. Taking the result from the transportation network model as the

input, the economic module was designed to translate those changes in travel time and distance into a desired output dollar amount representing the partial indirect economic losses. These indirect losses are investigated via their percent functionality along the time line: at day 1, day 3, day 7, day 30, day 90, etc. (Chen et al. 2005).

Although this study framework is developed to estimate the transportation related indirect earthquake losses as seen in previous studies (Gordon et al. 1998; Boarnet 1996), it has its differences. Both Gordon et al. (1998) and Boarnet (1996) conducted a survey to collect data from businesses and individuals regarding their losses related to transportation. In the Gordon et al. (1998) study, the aggregated indirect loss from the Northridge earthquake is estimated first with the input-output model. Then, the survey information regarding to the transportation related loss is applied to estimate the transport-related indirect loss. For this study, the impact on the transportation system is estimated directly from the focused source of losses, which in this instance is the damaged bridge information from the HAZUS software. Consequently, this transportation impact is employed as the input for the economic module in order to estimate the partial indirect loss.

The results of this research and defined approach are the outcome of a research project (Cooperative Agreement DTFH61-02-X-00009) at the University of Missouri-Rolla, funded by Federal Highway Association (FHWA). The complete details of this study can be found in Chen et al. (2005).

For the scope of this study, the estimated indirect loss covers only a portion of the total indirect loss from the damaged highway bridges. For future research, the partial indirect loss presented herein can be complemented by including other economic models. The increased travel cost or the partial indirect loss would create a ripple effect on the entire economic system,

such as increased prices for transportation service, and decreased spending budgets for consumers within the impacted region, among others. Economic models, such as the Computable General Equilibrium (CGE) model, can be applied to consider other sectors that contribute to the regional economic impact after a disaster (Chang et al. 2000; Rose and Lim 2002). The extended study framework for the total indirect loss of the study scenario, which is part of an on-going research effort, can be found in Tirasirichai and Enke (2006).

TRANSPORTATION NETWORK MODEL

Selection of the Transportation Network Model

As illustrated in Figure 1, the transportation network model is necessary to evaluate the impact of the earthquake damage on the highway network system as modeled using HAZUS-MH. This is achieved by modifying the data in the network link from the baseline transportation network. Following the bridge damage states output from HAZUS-MH, the network links in the baseline transportation network can be modified to simulate the damage state. The travel demand model is then run for each earthquake scenario using a modified road network to examine travel times and distances.

One approach used by the transportation planners to calculate the travel times and distances of a highway network is the urban transportation planning system (UTPS). There are different types of trips made in the transportation system. For instance, a work trip is a trip made from/to home to/from work place, while a non-work trip is a trip made during non-business hours and not related with individual's work. A UTPS is used to predict the number of trips made within an urban area by type (work, non-work, etc.), time of day (peak, off-peak, etc.), zonal

origin-destination (o-d) pair, and the routes taken through the transportation network by these trips. The final product of the UTPS is a predicted set of modal flows on links in a network. The UTPS, therefore, represents an equilibrium procedure in which the demand on the transportation system network is based on the network's performance characteristics. The major inputs to the UTPS are a specification of the activity system generating these flows, and the characteristics of the transportation system that will serve these flows (Chen et al. 2005).

Therefore, in order to make an analysis for any specific region, the required transportation network model must have the information about the transportation network inventory and travel demand information in significant detail. Moreover, it has to cover all the concern areas, including the St. Louis metropolitan area and the outside border areas. The border areas need to be included since people who live in those areas also spend time and are consuming network capacity while they are traveling into the internal areas. The Metropolitan Planning Organization (MPO) in St. Louis, by way of the East-West Gateway (EWG) Council of Government (http://www.ewgateway.org), provided the calibrated baseline transportation model for this study. Modifications to this baseline network model were made to represent the different damage states.

The EWG allowed the use of their facilities (hardware and software) for the transportation network modeling simulations. EWG also provided transportation data, transportation models, and forecasts for transportation scenarios the years 2000, 2004, and 2010 for the situation without an earthquake event. Year 2004 was selected as the baseline for this study to compare the changes in network performance due to a damaged network. This St. Louis regional travel demand model covers the entire eight county metropolitan areas, as well as the border areas. These areas are divided into a series of traffic analysis zones with different

demographic characteristics. These traffic analysis zones generate the corresponding travel trips from zone-to-zone which load the highway network, in addition to the trips coming into the study area.

East-West Gateway Transportation Network Model

The highway transportation network provided by EWG covers the entire study area and divides the area into small units, including the border zones, for a total of 1109 zones. The model gives the traffic data in detail of traffic from zone to zone, for each type of trip (work and non-work trip) and time period (peak and off-peak period). This EWG road network model covers all of the interstates, freeways, expressways, and other principal arterials in the study region, containing 13,529 links.

This EWG model uses MINUTP as the calculation software of the Urban Transportation Planning System (UTPS) and features modules for network development analysis. The MINUTP consists of a library of programs that provides the capability to perform the usual functions of traditional transportation planning, with regard to trip generation, distribution, and network assignment, given the user prepared link data, zone data, and friction factor data sets. Within the EWG St. Louis highway network model, cross-classification analysis is applied for trip generation, the gravity model for trip distribution, and the equilibrium assignment technique for network assignment (EWGCC 1997). Although, the MINUTP has the capability to predict the number of trips made within an urban area, in this study an important assumption about trip generation needed to be made - the amount of trip demand within the highway network before and after the earthquake scenario are the same. This assumption is due in part to the limitations of the availability of appropriate traffic databases and simulation models.

Other software used for supplemental parts of the model included ArcView™, Viper, and Cube. ArcView™ performs most geographic information system (GIS) tasks, such as mapping and spatial analysis, making it possible to locate and set up the scenario. Viper, which is a visual planning environment incorporating GIS functionality, is used as an editing tool of bridges/roads for different scenarios. Lastly, Cube, a travel demand package similar to MINUTP, is used only as an interpretation vehicle for the output files from MINUTP (Chen et al. 2005).

The baseline scenario (year 2004 regular situation without earthquake occurrence) and its associated dataset were provided by EWG. The land use data, housing unit, household, and employment information are used by EWG as input data to generate the travel demand model for the St. Louis metropolitan area.

Transitions from HAZUS-MH to the Transportation Model

To simulate the effect of the earthquake scenario on the transportation network, the EWG transportation model was modified based on the output of HAZUS-MH. Even though the EWG model is a suitable tool to analyze the HAZUS-MH output, the information transition process was still quite involved. The output from HAZUS-MH regards the damaged bridge, whereas the required information for the EWG model is the capacity of road links. Moreover, the damaged bridges need to be located onto the correct road link(s). The following steps are required in this transition process.

- _HAZUS-MH output data interpretation_: Determine which bridge structures within the study area have sustained damage in the earthquake scenario. Separate the bridges into groups based on their initial damage states. Select the bridges for indirect economic losses analysis based on the initial damage states and the probability of occurrence.

- *Transportation model data preparation*: The selected damaged bridges are mapped onto the EWG real-life road map/link. A damaged bridge will be represented in the EWG model by reducing the capacity of each affected link in the EWG model network and/or by modifying the number of lanes in the affected link. It is important to note that the network links in the transportation model may represent a combination of components (bridge or road) in that vicinity area and not an actual physical component at that location.

- *Transportation model implementation*: Modify the model's input road network by utilizing the MINUTP program to reduce the capacity of the links in the network that contain damaged bridges. Modify the input parameter files for each studied scenario run. Finally, execute the modified transportation network model to investigate travel time and travel distance for each earthquake scenario.

The most labor intensive task included preparing the input data for the EWG transportation model for the initial group of damaged bridges from HAZUS-MH. The first step was to decide on whether the bridges should be: (1) removed from the network in total for the transportation model scenario run (termed "initial damage state—bridge removal" method), (2) reduced in capacity directly after the event and then gradually restored back to full capacity over time (termed functionality – reduced bridge capacity" method), or (3) removed initially from the network and then restored over time back to full capacity. The investigators felt that the functionality method was a necessity to the project in order to gain a more accurate portrayal of the event-induced losses, so the functionality approach was used in the preparation of the earthquake scenarios. In the St. Louis scenario, bridges were removed from the network in order to reduce their capacity initially following the event to zero. Next, the initial damage had to be reduced over time to simulate the affects of repairs to the bridges, since the functionality

11

approach was selected for use. HAZUS-MH provides values for the Day 1, 7, 30, and 90

restoration percentages based on the Applied Technology Council (ATC) restoration curve

presented in ATC-13 and ATC-25. This recovery curve is developed based on California expert

opinion/experience in restoring the damaged bridges (ATC 1985). The Day 250, 350, and 400

values were produced by the investigators and input into HAZUS-MH following the same

restoration curves.

Final Output of Transportation Network

The EWG model output files give Vehicle Miles Traveled (VMT) and Vehicle Hours Traveled

(VHT) for each zone in the eight county bi-state areas. The result is for work trips and non-work

trips (both A.M. and P.M., peak and off-peak periods). Year 2004 results, in both VMT and

VHT, are used as the baseline for the network model. The results of the modified network model

under the earthquake scenarios are then compared to this baseline. From this data, the differences

of VMT and VHT that result from the earthquake will be captured.

ECONOMIC MODULE

Economic Module Design

The objective of the economic module is to translate increases of travel distance and time within

the transportation network into a dollar figure. The indirect loss economic module is illustrated

in Figure 2. By developing generic equations to estimate the value of travel time and cost of

travel distance, and employing the changes in travel time and distance (which are outputs from

the transportation network simulation model), the expected partial indirect economic loss from

each earthquake scenario can be estimated. The loss for each route in the study area is calculated separately and then summed together to produce the total partial indirect loss value.

The model has been developed to estimate only the expected or average partial loss that would occur without considering variation. It is also purposely designed to be easy to understand and update. To obtain the most accurate estimation, all information used to develop the model requires regional information from reliable public sources, such as the Census Bureau, the Department of Transportation (DOT), and the Bureau of Transportation Statistics.

Value of Travel Time and Travel Distance

There are many studies that consider the estimation of the value of travel time and travel distance. Most of these studies (U.S. DOT 1997; Frye 1973; Kawamura 1999; Thomas 1968; Thomas and Thompson 1970) are looking at these values from the perspective of travel time and/or distance savings with the purpose of performing a cost benefit analysis of a new road project. Among these researches, there are only a few (Waters et al. 1995; Gunn 2001) which discuss these values from the perspective of loss due to increases in travel time and/or distance. From the perspective of loss, the value of time and distance will be weighted more than the travel time or distance that could be saved.

Travel time is an intangible item, making it difficult to value. Many approaches have been developed to estimate the cost of travel time. Some studies (Thomas 1968; Thomas and Thompson, 1970) use a survey method to find the relationship between the value of time and the demographic data. The survey is typically conducted to collect the value of time for each individual and their demographic data, such as income and trip length, among others. Then, an empirical model is developed based on this survey data. A behavioral study approach can also be

applied (Erhardt et al. 2002; Richardson 2001). This approach infers the value of time from situations in which drivers face time and monetary tradeoffs. A logic model is then applied, along with a mode choice process, to develop the mode choice utility empirical model, showing the relationship of mode utility with travel time and price variables. By finding the ratio of these two coefficients in the mode utility function, the value of time is then estimated (Kawamura 1999). Since there are limitations in the time frame of this study, conducting the survey is not an option. The value of time for this study was developed based on literature review and reliable results from the existing studies.

For part of the travel distance cost, a vehicle operating cost is applied, mainly consisting of fuel cost, maintenance cost, repair cost, and insurance cost (AAA 2003; Curry 1972; Waters et al. 1995). These costs are strongly related to the vehicle travel distance. The composition of the travel distance cost for this project was modified from previous studies to fulfill the study objective. Each component of the cost was selected locally to focus on the study region.

Based on the major studies in this area (U.S. DOT 1997; Mackie et al. 2003; VTPI 2003), the values of travel time and distance are different for the various types of trip. The travel trip of the study can be classified by the trip purpose as a work trip, non-work trip, or commercial trip. Work trips and non-work trips are arranged into the same group as the commuting trip. The commuting trip is a trip made by a person during his/her non-working hours, whereas the commercial trip is a trip where travel time is "on the clock" from the employer's point of view. In this study, it was assumed that all commercial trips are made only by freight companies.

Value of travel time delayed and increased travel distance was developed based on the regional information to be appropriated with the regional partial indirect loss estimation. For the commuting trip, the value of time delay was estimated based on a review of the literature and the

estimation was decided to be at 50 percent of the traveler's income, while the travel time value for a commercial trip was estimated following the approach suggested by Waters et al. (1995). Waters' approach is modified and extended to be able to estimate the value of increased travel distance for both commuting and commercial trips. The results of these numbers are shown in Table 2.

Partial Indirect Loss Estimation

To aid in the modeling and reduce complexity, some assumptions were made in the partial indirect loss estimation. First, the percentages of different types of trip (work trip, non-work trip, and commercial trip) are the same for every zone throughout the study area. The number of passengers per vehicle is assumed to be the same for every zone, and all passengers are adults. The number of passenger per vehicle for the commuting trips is represented by the weighted average of different types of commuting trips. It is assumed that there is only the driver in the vehicle for the commercial trip. Moreover, some assumptions from the calculation of time and distance value are vital to the partial indirect loss estimation results. Those assumptions include the vehicle highway mileage travel per year and the number of annual working hours. The entire group of assumptions produces a low indirect loss estimate since not all the factors affecting the transportation travel are being considered due to the complexity of the problem.

The partial losses due only to delayed travel time only will be different from zone to zone in the study area since the travel time value is dependant on the income level. A weighted average of each zone income is used to represent the income for every person in that zone. It seems reasonable to compute loss estimates for each zone. However, the partial indirect loss must be separately calculated for each route instead of for each zone. The reason being that the

output from the highway network matrix shows the total amount of travel time from zone to zone during a certain period of time. For example, one value in the output matrix will present the total amount of time consumed by all trips from zone A to zone B during the peak hours. Caution is needed for the time value for each zone and can not be applied to all the trips from that zone to the others, which is explained in Figure 3. Consider the trips that occur between zone A and zone B. The time value for a person in zone B could be used when the trip is made by a person who originally lives in zone B. However, all trips made from zone B to zone A are not only made by individuals who live in zone B, but also by the returning travelers who originally live in zone A. Therefore, assumptions have to be made. First, the time value of each zone will be used only for the trips made within that zone. Second, for the trips between each pair of zones, the average time value of that pair will be applied as the time value for those trips. This results in a loss calculation for each travel route instead of for each zone.

Considering the available input and the desired output, the total partial indirect loss is simply the summation of increased indirect costs for each travel route. These partial indirect losses will be shown in year 2004 US dollars on the basis of an hourly average during peak and off-peak periods along the time horizon using the same format as the output obtained from the EWG transportation model. The MatLab® software package was used as the calculation tool due to its capability to handle large matrix/array operations.

STUDY RESULTS

Study Scenario Selection and Preparation

In addition to defining the study area, the appropriate earthquake scenario(s) had to be selected to conduct the loss estimation. Each study scenario was selected based on a review of deterministic, historic and prehistoric, and probabilistic earthquakes that would critically affect the St. Louis transportation infrastructure. A total of three scenarios were selected to represent high, moderate, and low probability events for damage in the St. Louis study area. The St. Louis scenario (Mw 7.0) represents the low probability but high consequence end of the loss range. The Germantown scenario (Mw 7.0) represents a moderate probability event with a moderately high consequence due to its close proximity to St. Louis and its large magnitude. Lastly, the New Madrid scenario (Mw 7.7) represents high probability based on its historic significance, but near the low consequence end of the loss range due to its distance from St. Louis.

Some of the damaged bridges identified by the HAZUS-MH had to be ignored in the indirect loss estimation. Only significant bridges were selected based on their initial damage state and the defined damage state cutoff point. The cutoff point for each study scenario is defined as follows:

- *St. Louis scenario*: at least 75% probability of having an initial damage state of "complete". This was selected since it has the least probability of occurring out of three scenario runs.
- *Germantown scenario*: at least 50% probability of having an initial damage state of "moderate" or greater. The value of 50% was selected to reflect the greater chance of the earthquake event occurring.
- *New Madrid scenario*: at least 30% probability of having an initial damage state of "slight" or greater. This results in the least amount of damage to the bridges, although the earthquake event has the greatest chance of occurring.

EWG Transportation Network Result

MINUTP runs were created for days 1, 30, 90, and 250 after the earthquake event. There were additional runs of St. Louis and Germantown scenarios for day 350 and day 400. These days were selected since they were considered to provide a good representation of the ATC-13 recovery curve. The results of all runs are shown in Figures 4 and 5.

The trend in increased travel time and distances is high the very first day after the incident occurrence, as expected. Afterwards, the differences exponentially decrease until the full recovery of the network to a baseline condition. The change in distances traveled for the different scenarios were not expected to increase much due to the redundancy in the transportation network and the limited number or bridges affected, showing just a small variation around an average distance.

Economic Module Results

Based on the provided input, which is the output from the EWG transportation model, the time horizon for the analysis was considered at days 1, 30, 90, 250, and 500 after the earthquake incident. The extension to 500 days was added to consider the assumption that for this number of days there are no additional indirect losses since the highway system would be fully restored. The results obtained from this calculation process are the amount of partial indirect loss on an hourly basis at one specific time after the incident. Next, the weighted average between peak and off-peak periods during a day is used to represent the daily partial indirect losses. Since the partial indirect loss estimation for the Germantown and New Madrid earthquake scenarios had little impact due to the negligible bridge damage in the St. Louis metropolitan area, only the daily indirect loss results of the St. Louis scenario are provided in detail (see Figure 6).

The overall partial loss for each scenario is the integration of the daily partial loss from the incident day through the day when the system is fully recovered. In other words, the overall indirect loss can be approximated by the area under the graph of daily partial indirect loss from day 1 through day 500 after the incident. Following this approach, the partial indirect loss for each scenario is shown in Table 3.

The number estimated by other studies (Boarnet 1996; Gordon et al. 1998; Ho 2001; OTA 1995; Petak and Elahi 2000) for the previous earthquake incidences vary, even for the same incidence. For example, the damage of Northridge earthquake in 1994 was estimated to range from $25.5 billion to $53.3 billion (2004 US dollars) for the direct loss, and from $7.6 billion to $9.56 billion (2004 US dollars) for indirect loss. The direct loss in those studies included the loss in infrastructure, including highways, buildings, and residences, whereas the indirect loss included all business interruptions. Since the scope of this study is only for the cost to recover the damaged bridges along the highway, along with the indirect cost resulting from those damaged bridges, the losses from the other studies are much larger than the losses estimated by this study. Moreover, the partial indirect losses were compared with the direct loss estimation results for the same simulated earthquake scenario (Luna et al. 2007). The percentage numbers in Table 3 show a significant quantity of partial indirect loss relative to the direct loss.

Finally, the partial indirect loss numbers estimated in this study are based on the recovery curve from the ATC-13 recovery curve. The construction companies and related organizations in California have more experience dealing with earthquakes and their aftermath when compared to the Midwest. Therefore, the actual loss for the St. Louis scenario will likely have a longer effect and a larger total magnitude than the estimated figures. The expected actual loss due to an

earthquake for St. Louis should be higher and would produce a curve in the region above the one computed for this study, as shown in Figure 7.

CONCLUSIONS

This study suggests an approach to measure indirect loss, which is a dollar figure often overlooked by policy makers. The scope of the model in this study is to capture the loss produced by damage to bridges in the highway network. This partial indirect loss is only a portion of the loss from the earthquake scenario, and the calculations performed have considered a limited amount of factors closely related with the transportation time delays and distances traveled. The estimated partial indirect loss for the study scenario is approximately $703 million dollars, which in comparison is about 55% of the direct loss for the same scenario. The numbers from this study will only conservatively represent the smallest partial indirect loss figure of the incident. Nonetheless, comparison of the partial indirect loss to the direct loss still clearly illustrates the significance of the partial indirect losses in both magnitude and affected area. Therefore, it is important to consider not only the direct loss, but also the indirect loss of any earthquake situation under study.

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Tables

Table 1. Loss Estimation from Earlier Studies (adapted from Rowshandel et al. 2000)

Earthquake	M	Total Loss[a]
1971 San Fernando	6.7	2,200[b]
1979 Imperial Valley	6.5	70[b]
1983 Coalinga	6.4	18[b]
1987 Whitter Narrows	5.9	522[c]
1989 Loma Prieta	7.0	10,000[d]
1994 Northridge	6.7	46,000[e]
1992 Petrolia	7.0	80[c]
1992 Landers	7.6	120[c]
1999 Hector Mine	7.4	Minor

Notes:

[a] Estimates are in millions dollar (Year 2000 dollar value)

[b] Estimate is from FEMA

[c] Estimate is from U.S. OTA

[d] Estimate is from NRC

[e] Estimate is from California Governor's OES

Table 2. Value of Time Delayed and Increased Travel Distance

Value of	Commuting Trip	Commercial Trip
Time Delayed (hour)	60% of income	$29.60
Increased Distance (km)	$0.28	$0.70

Note: Estimates are in Year 2004 dollars

Table 3. Partial Indirect Costs for each Earthquake Scenario

Earthquake Scenario	Partial Indirect Loss ($ million)	Percentage to Direct Loss
St. Louis	700	81%
Germantown	11	6%
New Madrid	13	19%

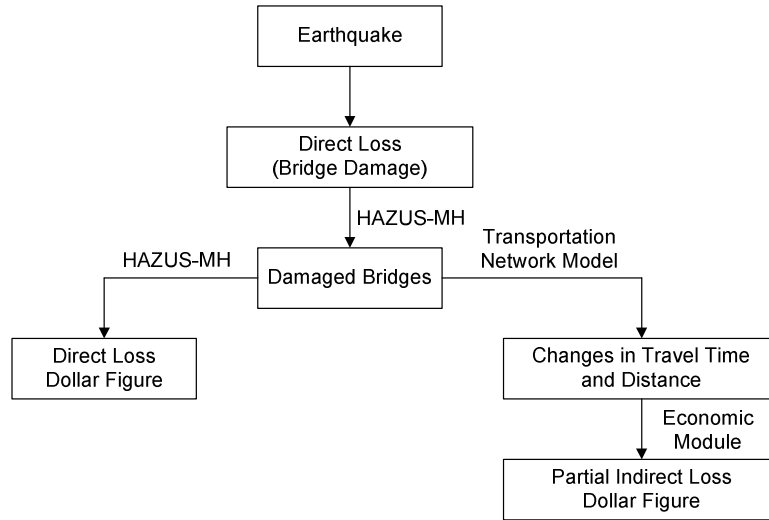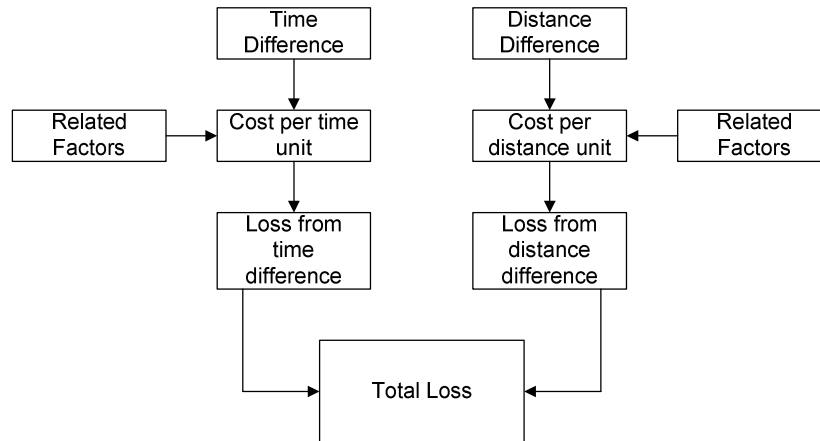Note: Estimates are in Year 2004 dollars

Figures

Fig. 1. Study Framework Diagram

$$\text{Total Partial Indirect Loss} = \sum_{i=1}^{n} \sum_{j=1}^{n} \text{Loss from increase travel time of route } ij$$

$$+ \sum_{i=1}^{n} \sum_{j=1}^{n} \text{Loss from increase travel distance of route } ij$$

where: i = Route origin zone number

j = Route destination zone number

n = Total number of zones in the study area
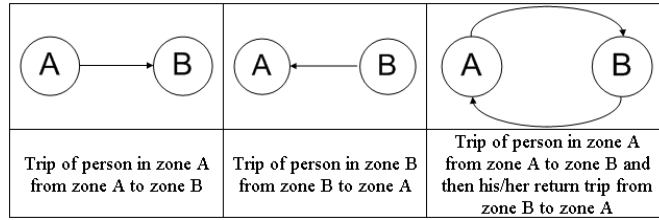
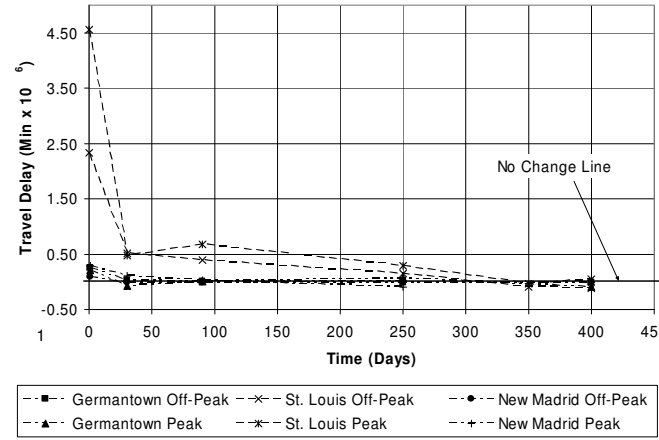**Fig. 2.** Indirect Economic Loss Module

Fig. 3. Travel Route Illustration

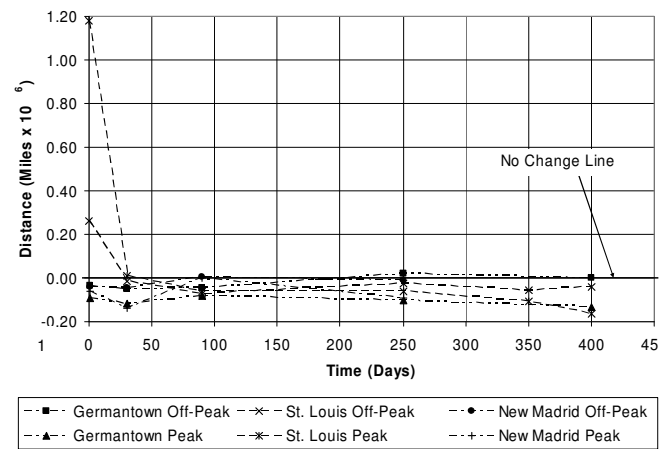**Fig. 4.** Difference in Peak and Off-Peak Travel Time for the Study Region due to the Simulated Earthquake Events

Fig. 5. Difference in Peak and Off-Peak Travel Distances for the Study Region due to the Simulated Earthquake Events
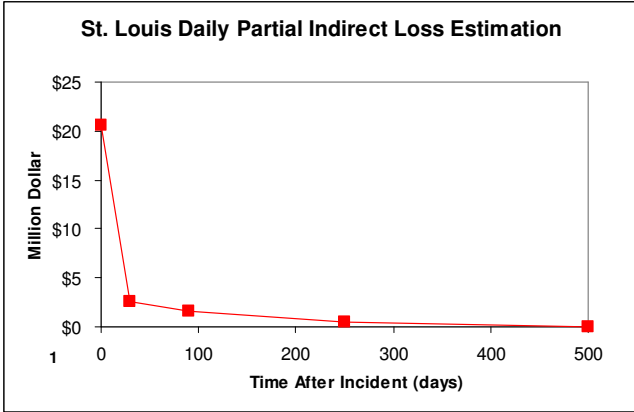
St. Louis Daily Partial Indirect Loss Estimation

Fig. 6. St. Louis Scenario Daily Partial Indirect Loss
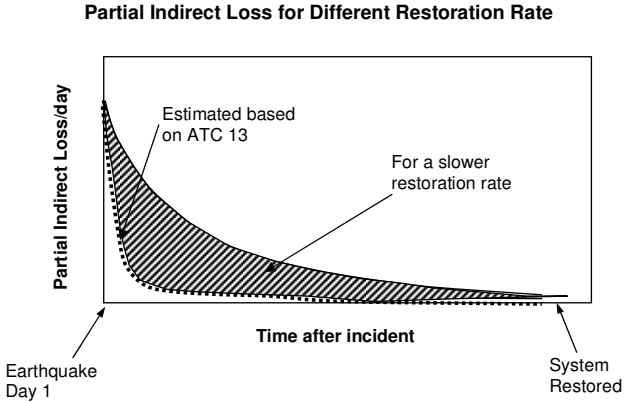
Partial Indirect Loss for Different Restoration Rate

Fig. 7. Estimated and Expected Actual Partial Loss Smoothing Curves