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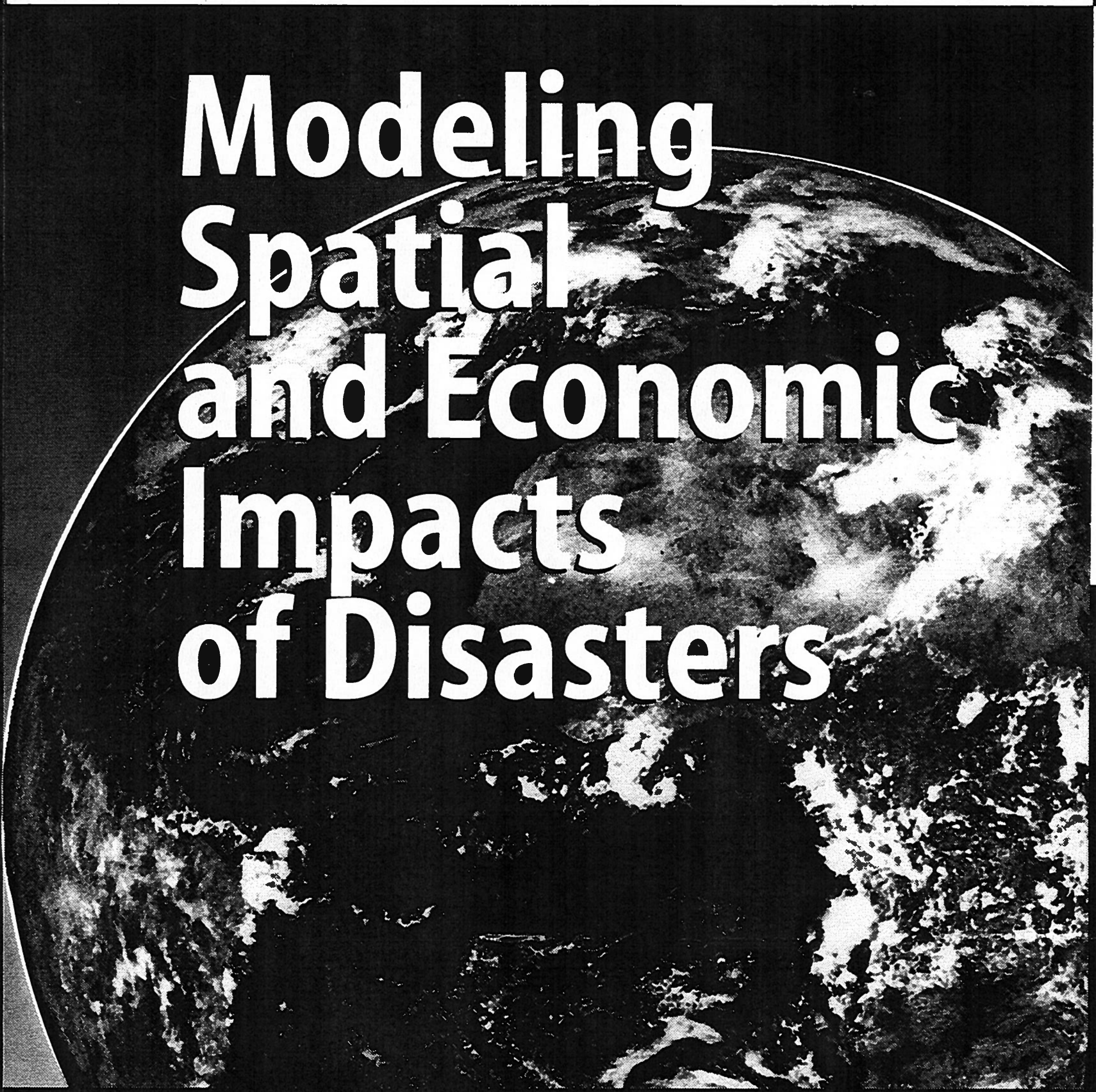

Modeling Spatial and Economic Impacts of Disasters

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Yasuhide Okuyama · Stephanie E. Chang
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Modeling Spatial and Economic Impacts of Disasters

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11 Earthquake Disaster Mitigation for Urban Transportation Systems: An Integrated Methodology that Builds on the Kobe and Northridge Experiences*

Peter Gordon,[1] James E. Moore II,[2] Harry W. Richardson,[1] Masanobu Shinozuka,[3] Donghwan An[4], and Sungbin Cho[5]

[1] School of Policy, Planning, & Development and Department of Economics, University of Southern California, USA
e-mail: pgordon@usc.edu, hrichard@usc.edu
[2] Department of Industrial and Systems Engineering and School of Policy, Planning, & Development, University of Southern California, USA
e-mail: jmoore@usc.edu
[3] Department of Civil and Environmental Engineering, University of California, Irvine, USA
e-mail: shino@uci.edu
[4] Department of Agricultural Economics and Rural Development, Seoul National University, Republic of Korea
e-mail: dha@snu.ac.kr
[5] School of Policy, Planning, & Development, University of Southern California, and Imagecat, USA
e-mail: sungbinc@usc.edu and sc@imagecatinc.com

11.1 Introduction

11.1.1 Applied Economics and Policy Analysis

Around the world, natural disasters kill thousands each year and inflict billions of dollars in damage. Better analysis has the potential to save lives and resources on a large scale. One of the most important applications of economic analysis is to the evaluation of proposed projects and policy measures, usually benefit-cost analysis. A related but different approach involves regional economic impact analysis. Whereas benefit-cost analysis can be used to rank policy measures in terms of their efficient use of resources, impact analysis offers a reading of how far these measures deviate the local economy from current performance levels. The simplest examples are the widely reported multiplier analyses wherein proponents of certain projects (sports stadia, convention centers, etc.) claim that some multiple of annual expenditures will enhance

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the regional economy because of various ripple effects. Our claim in this research is that some available economic impact models when properly modified and elaborated lend themselves to the problem of determining plausible evaluations of earthquake mitigation and reconstruction policies for metropolitan areas.

A review of the literature (Cho *et al.*, 2001) shows that there has been limited attention given to the socioeconomic impacts of earthquakes. Progress in economic impact research is recent. Most of the research on earthquakes has been in the engineering and geological fields. Earthquake engineering is an established field, but integrating the economic impacts of earthquakes with engineering models remains a challenge.

The most widely used models of regional economic impacts are versions of interindustry models. These trace intra- and inter-regional shipments at a high level of industrial disaggregation. They only account for losses via backward linkages, because they are demand driven.

11.1.2 Integrating Regional Economic Modeling and Urban Earthquake Policy Analysis

A considerable earthquake engineering literature devotes itself to the estimation of "direct" damages from a past or expected natural disaster. These estimates become benchmarks for calculating possible loss reductions (benefits), which can be weighed against the costs of achieving these reductions. It is now widely recognized that this approach is inadequate because these losses also have a time dimension: for how long will the services of the facility be diminished? The latter are often labeled as "indirect" effects, a possibly misleading descriptor because indirect has a slightly different meaning in the regional economic impact assessment literature. Researchers in this field have recently adopted "business interruption" or "loss of functionality" as descriptors of many of these effects.

Yet, there are other effects to consider. It is important to be comprehensive because policy analysis should begin with a full accounting of losses before any plausible policy recommendations are made. A full accounting supposes the ability to trace the full effects of the losses of any facility through the regional economy. Interindustry economic analysis, usually input-output (IO) analysis, has been applied to aspects of this problem for many years. The appeal of this approach is that the interdependence of shipments is depicted in considerable detail. Yet, it may seem ironic that the medium over which shipping occurs is usually absent from these models. Our conjecture is that, for the case of highways, the fact that highway services are not obtained on a contractual basis, with payment for these services normally treated as an indirect cost to firm operations (taxes and license fees) rather than being associated with individual shipments, explains the paradox. This institutional fact of life, however, does not absolve modelers and policy makers from attempting to integrate models that determine shipping costs with models that estimate the associated production costs. In terms of operational models, this compels us to fuse regional input-output models with regional highway network models. That effort also opens the possibility of merging earthquake engineering models of seismic activity and structures into the framework.

The following sections of this report provide the details of aspects of model integration that were accomplished. We also discuss the applications of the resulting model to: i) the simulation of the full costs of a hypothetical earthquake; ii) the determination of bridge reconstruction costs; iii) the calculation of plausible bridge reconstruction budgets, determined in light of expected production shortages and bottlenecks.

11.2 Southern California Planning Model 2 (SCPM2)

11.2.1 Background

Regional economists have invested much time examining interindustry models. The details of intersectoral linkages in these models are useful for exploring regional economic structure. However, this approach has not permitted an adequate treatment of transportation costs, not all of which are transacted because most roads are publicly provided. This problem has recently been addressed at the national level by the Bureau of Transportation Statistics effort to create Transportation Satellite Accounts (Han and Fang, 2000).

Spatial elaborations of input-output and related approaches require explicit treatment of the resources consumed by flows between origin-destination pairs (Moses 1960, Okuyama *et al.* 1997). Explicit representation of the transportation network is usually not necessary in multiregional approaches. It is another matter at the intrametropolitan level, because congestion dominates line-haul costs.

Southern California Planning Model 1 (SCPM1) by Richardson *et al.* (1993) combined a metropolitan level input-output model with a Garin-Lowry model to spatially allocate induced economic impacts. This operationalized spatial input-output analysis at the intrametropolitan level. That model did not treat the transportation network explicitly. Congestion effects were ignored, and transportation flows were exogenous.

Integrating a transportation network into SCPM1 provides important opportunities. Distance decay relationships (destination choice) can be endogenized, permitting an improved spatial allocation of indirect and induced economic impacts. Also, this integration makes it possible to better account for the economic consequences of changes in transportation network capacity.

Our interest is in the regional economic consequences of earthquakes, which result in some of the most dramatic changes in regional economic and infrastructure capacity. The costs-of-earthquakes literature emphasizes the measurement of structure and contents losses. More recently, social-science-based research on earthquakes has addressed the measurement of business interruption costs (Gordon, Richardson, and Davis, 1998; Rose and Benavides, 1998; Boarnet, 1998). Yet, there are still few studies that examine the role of infrastructure and its interactions with the metropolitan economy.

Several research questions motivated this work. First, we wanted to integrate regional economic, transportation, bridge performance, and other structural response models in a way that respects feedback relationships between land use and transportation. Second, we sought to apply such integrated, operational models to the problem of estimating the costs of a large earthquake. Third, we wanted to account for the costs of damage to infrastructure, with special attention to bottlenecks and shortages that are created in the course of large-scale reconstruction. Further, because "all politics are local," we wanted to describe these costs and benefits at the submetropolitan level.

To accomplish this, we integrated a) bridge and other structure performance models, b) transportation network models, c) spatial allocation models, and d) inter-industry (input-output) models. We then used the integrated model to begin analysis of various bridge reconstruction scenarios.

The Southern California Planning Model (SCPM1) was developed for the Los Angeles metropolitan region. The study area includes Los Angeles, Orange, Riverside, San Bernardino and Ventura counties. The area covers more than 35,000 square miles. The 2000 population of the five-county area was over 16.3 million. At this time, data for the urbanized portions of the metropolitan area were not yet available. In 1990, the urbanized portions extended to 1,966 square miles; population density in the urbanized area was about 5,801 people per square mile, the highest in the U.S. The urbanized area is described in terms of SCAG's 1527 disaggregate traffic analysis zones (TAZs). The regional highway network includes 22,244 links.

Table 11.1 provides additional recent aggregate data describing the study area. The total households in the area were 5.4 million in 1998 (US Bureau of Census). The non-farm employment in the SCAG region was over 5.8 million in 1997. Personal income in the area was $329.6 billion and per capita personal income was $21,542 in 1994. 21.6 percent of income was goods-related and 78 percent of income was service related. The employment distribution across industry sectors is: 34.3 percent in services, 16.4 percent in manufacturing, 13.3 percent in government, 9.6 percent in retail, and 7.3 percent in FIRE. International exports from the five-county area have been reported to be $35.7 billion in 1996 (Exporter Location Series, US Bureau of the Census). Our analysis suggests, however, that this is a significant underestimate (Gordon and Richardson, 1999).

Table 11.1 Socio-Economic Profile, SCAG Five-County Area

County	Population (persons)	Households (1,000)	Employment (paid employees)	Total Personal Income ($1,000)	Per Capita Income ($)	Land Area (square miles)
Year	2000	1998	1997	1994	1994	1990
Los Angeles	9,519,338	3,136.6	3,693,537	197,289,098	21,562	4,060
Orange	2,846,289	941.0	1,212,689	64,892,666	25,516	790
Riverside	1,545,387	1,037.9ª	319,904	25,086,809	18,543	7,208
San Bernardino	1,709,434	ª	406,859	26,477,943	17,043	20,062
Ventura	753,197	239.9	211,591	15,899,444	22,625	1,846
Five-County	16,373,645	5,355.4	5,844,580	329,645,960	21,542	33,966

Source: U.S. Census Bureau's state and county quick facts (http://quickfacts.census.gov/qfd/)
Notes: a. Data for Riverside-San Bernardino PMSA
b. Values of employment (private nonfarm employment) and land area from People QuickFacts for each individual county. Values of population come from USA Counties General Profile for each individual county. Values of total personal income and per capita personal income are from Local Area Personal Income data of Bureau of Economic Analysis (BEA).

The model allocates impacts in terms of jobs or the dollar value of output to 308 sub-regional (municipal) zones. Analysis of Northridge earthquake business interruption effects utilized SCPM1 (Gordon, Richardson, and Davis, 1998). That model was driven by reduced demands on the part of damaged businesses, as ascertained from survey results.

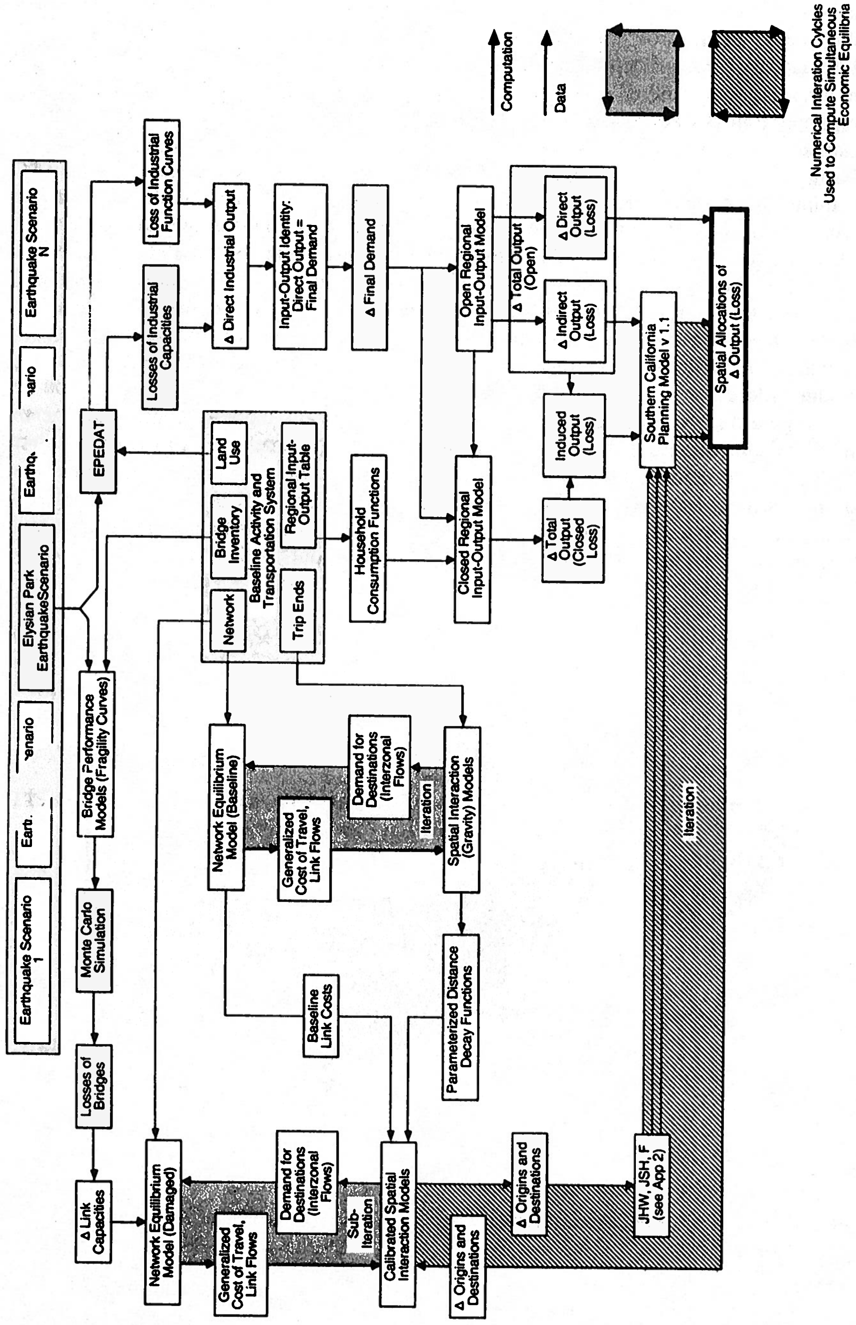

Figure 11.1 Summary of the Southern California Planning Model 2 (SCPM2)

In this exercise, we focused on a hypothetical earthquake, a magnitude 7.1 maximum credible earthquake (MCE) event on the Elysian Park blind thrust fault. In this case, results of structure damage to businesses, as developed by EQE International's Early Post-Earthquake Damage Assessment Tool (EPEDAT), were used to drive a new version of SCPM, SCPM2, that has been improved to include the regional transportation network. EQE's EPEDAT is a GIS-based earthquake loss estimation program that estimates ground motion, structural damage, and direct business interruption losses associated with a specific earthquake (Eguchi *et al.*, 1997; Campbell, 1997). EPEDAT predicts, among other values, the lengths of time for which firms throughout the region will be non-operational. This allows the calculation of exogenously prompted reductions in demand by these businesses. These are introduced into the inter-industry model as reductions in final demand (Isard and Kuenne, 1953). Explicit treatment of the transportation network made it possible to model the concurrent impact of transportation cost changes on the activity system, including reductions in regional network capacity resulting from large numbers of bridge failures.

Figure 11.1 summarizes our approach. Engineering models predict damage to transportation structures by location for the Elysian Park scenario. EPEDAT predicts spatial loss of industrial function. The I/O model translates this production shock into direct, indirect, and induced costs, and the indirect and induced costs are spatially allocated in terms consistent with the endogenous transportation behaviors of firms and household. See Cho *et al.* (2001) for a detailed description of SCPM2.

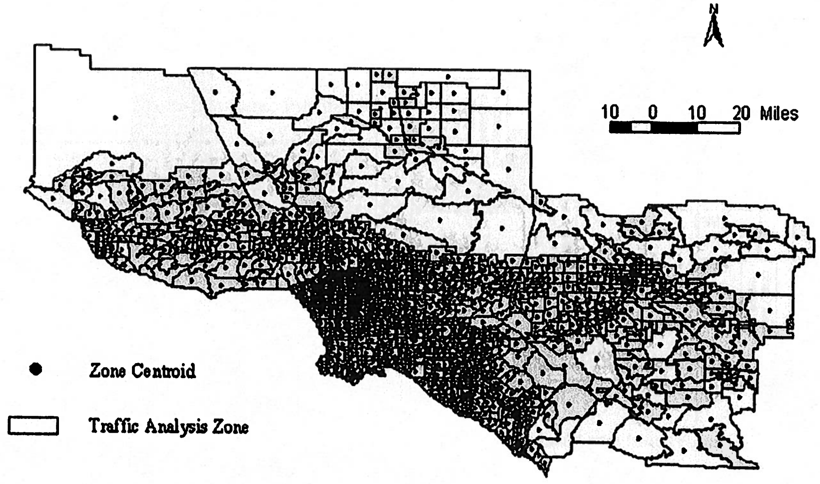

Figure 11.2 1,527 Southern California Association of Governments (SCAG) Traffic Analysis Zones

Implementing this approach is a data intensive effort. SCPM2 aggregates the Southern of California Association of Governments (SCAG) 1,527 traffic analysis zones (see figure 11.2) into 308 political jurisdictions, and aggregates to 17 the 515 sectors represented in the Regional Science Research Corporation's PC I-O model Version 7 (Stevens, 1996) based on the work of Stevens, Treyz, and Lahr (1983). SCPM2 treats the transportation network explicitly, endogenizing otherwise exogenous matrices describing the travel behavior of households, achieving consistency across network costs and origin-destination requirements, and better allocating indirect and induced economic losses over zones in response to direct earthquake losses to industrial and transportation capacity. Making distance decay relationships and congestion endogenous also endogenizes the spatial allocation of indirect and induced economic losses.

Our goal was to model the effects of earthquakes on industrial capacity and system-wide transportation demand and supply. We also wanted to measure as fully as possible the economic impacts associated with both of these effects. Our first step was to compute a pre-earthquake baseline that is consistent with respect to equilibrium network costs, network flows, and inter-zonal flows and origin-destination requirements. The information needed to model an internally consistent baseline is also sufficient to treat changes in configuration of the network and the activity system. Following an earthquake, there will be losses of network capacity and simultaneous losses of industrial capacity. The former reduces transportation capacity and raises costs. The latter will reduce demands imposed on the network. The bridge performance models and building fragility curve analysis (EPEDAT) ascribe consistent losses of both types to particular earthquake scenarios. The spatial interaction elements of our approach made it possible to capture the changes in transportation requirements associated with changes in network performance. These changes and changes resulting from earthquake damage to industrial facilities were treated simultaneously and consistently.

11.2.2 Application: Towards Determining the Full Costs an Elysian Park 7.1 Maximum Credible Event

SCPM2 was applied to the Los Angeles metropolitan area for the scenario defined by a maximum credible earthquake (magnitude 7.1) on the Elysian Park thrust ramp. This Elysian Park scenario was selected on the basis of its potential to produce major damage and casualties; despite this, the fault has received little systematic attention. Also, the annual probability of an earthquake associated with this fault is relatively high within the Southern California fault system. Like the 1994 Northridge earthquake, the Elysian Park scenario occurs on a blind thrust fault. While the maximum size earthquakes that seismologists believe are possible on the blind thrust faults are lower than those on, for example, the San Andreas Fault, they are expected to have the potential to result in more severe damage because of their proximity to metropolitan Los Angeles. The planar earthquake source representation for the Elysian Park event varies in depth from 11.0 to 16.0 km below the surface. The surface projection of this source includes a broad, densely populated area of central Los Angeles County, including downtown Los Angeles. Figure 11.3 provides a map of predicted peak ground accelerations by 1990 census tract for this event.

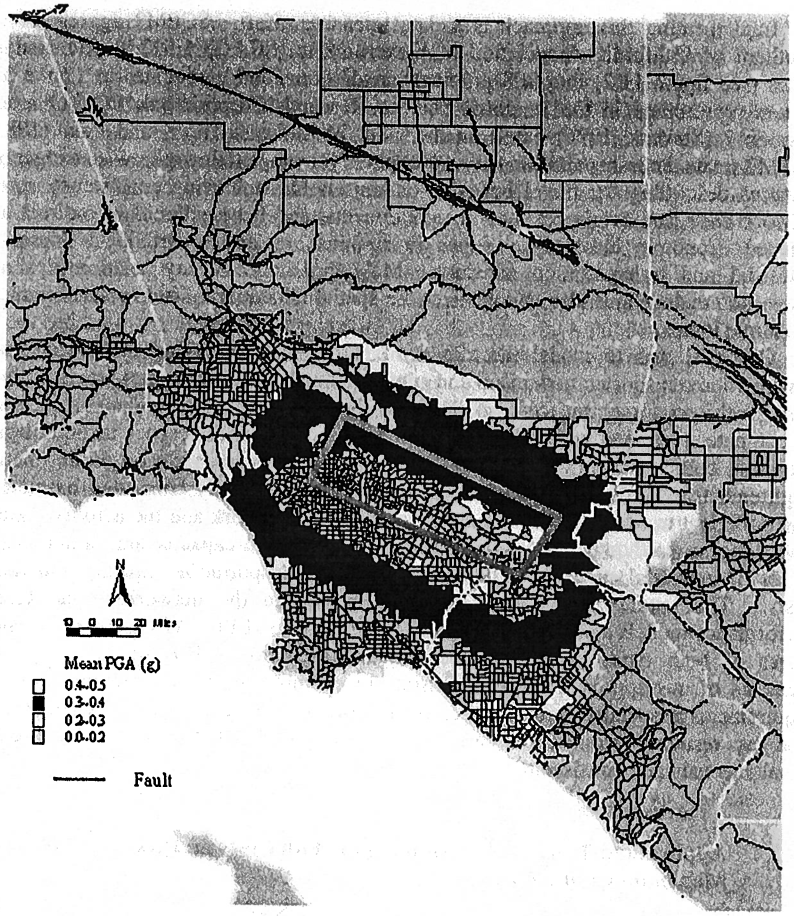

Figure 11.3 - Predicted Peak Ground Accelerations for a Magnitude 7.1 Earthquake on the Elysian Park Blind Thrust Fault

Bridge fragility curves give the probability distribution of bridge damage states conditioned by bridge type and earthquake event, in this case the Elysian Park scenario. These damage states were defined in terms of a bridge damage index (BDI) ranging from 0 (no damage) to 1 (collapse). BDI intervals are mapped to each of four damage states as shown in table 11.2.

Empirical fragility curves (Shinozuka, 1998 and 1999) are developed on the basis of bridge damage records made after the 1994 Northridge Earthquake. These curves are expressed in the form of two-parameter lognormal distribution functions. The two parameters (median and log-standard deviation) are estimated via a maximum likelihood method. The Peak Ground Acceleration (PGA) is used to characterize the intensity of the seismic ground motion, although use of other intensity measures such as Peak Ground Velocity (PGV), Spectral Acceleration (SA), Spectral Intensity (SI), and Modified Mercalli Intensity (MMI) are reasonable.

$$L=\prod_{i=1}^{N}[F(a_i)]^{x_i}[1-F(a_i)]^{1-x_i} \tag{11.1}$$

where L = likelihood;
$F(a_i)$ = the fragility curve for a specific bridge damage state;
a_i = is the PGA value to which bridge i is subjected,
x_i = 1 or 0, depending on whether or not the bridge achieves damage state $F(a_i)$ under PGA = a_i; and
N = the total number of bridges inspected after the earthquake.

Under the lognormal assumption, *F(a)* takes the analytical form

$$F(a)=\Phi\left[\frac{\ln\left(\frac{a}{c}\right)}{\xi}\right] \tag{11.2}$$

where a = PGA value,
c = median,
ζ = logstandard deviation, and
$\Phi[\bullet]$ = is the standardized normal distribution function.

The two parameters c and ζ in equation (11.2) are computed as c_0 and ζ_0 maximizing the log of the likelihood function, ln*L*, and hence *L*.

$$\frac{d\ln L}{dc}=\frac{d\ln L}{d\zeta}=0 \tag{11.3}$$

This optimization is straightforward. This procedure produces fragility curves classified by bridge damage state.

Table 11.2 Bridge Damage States, Bridge Damage Index, and Fragility Curve Parameters

Bridge Damage State / Fragility Curve	> BDI Lower Bound	≤ BDI Upper Bound	Median	Log Standard Deviation
Minor Damage	0.050	0.200	0.83	0.82
Moderate Damage	0.200	0.525	1.07	0.82
Major Damage	0.525	0.850	1.76	0.82
Collapse	0.850	1.000	3.96	0.82

A family of four separate fragility curves for (1) at least minor damage, (2) at least moderate damage, (3) at least major damage, and (4) collapse states is estimated simultaneously on the basis of the PGA values and damage states reported by California Department of Transportation engineers for 1,998 bridges damaged by the Northridge Earthquake. Each Fragility curve describes the cumulative probability of achieving a given damage state as a function of PGA, consequently the fragility curves for the four damage states never intersect (see figure 11.4). The medians and log-standard deviations of these fragility curves are given in table 11.2.

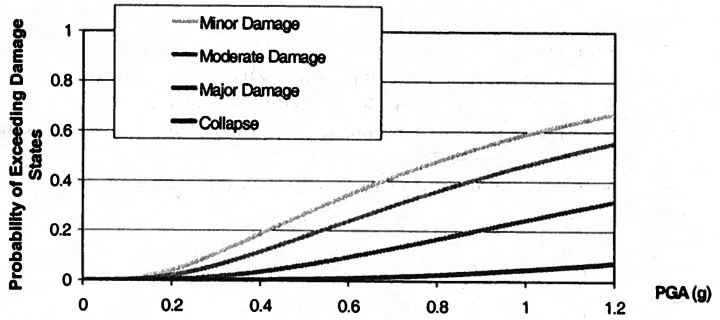

Figure 11.4 Bridge Fragility Curves Estimated from Caltrans Northridge Earthquake Data

From a network management perspective, the key operational question is "At what bridge damage index value should the bridge be closed?" Our approach made it possible to systematically investigate the cost implications of alternative bridge closure criteria.

The approximate midpoints of the bridge damage index intervals associated with moderate and severe damage states are 0.3 and 0.75, respectively. We treated these values as the most conservative and riskiest BDI thresholds that transportation authorities are likely to accept as bridge closure criteria. A conservative, safety oriented policy would close damaged structures to traffic, including bridges with a damage index ≥ 0.30. This would increase delay and other transportation costs. A less risk averse policy intended to emphasize an emergency focus on maintaining regional economic function would leave moderately damaged structures open, closing only bridges with a damage index ≥ 0.75. No authority would open the most dangerous structures.

Earthquakes induce changes in industrial production due to effects on building stocks, particularly factories, warehouses, and office buildings. Damage to production facilities was translated into an exogenous change in final demand. Building damage causes direct loss in industrial production. EPEDAT's loss-of-function curves convert damage to building stocks to loss of production by zone and sector. The loss-of-function curves structural damage states to business closure times and direct business interruption (production) losses. Inputs are commercial and industrial building damage estimates from EPEDAT, expressed as the percent of structures in each of four damage states by use class and by each of the 308 SCPM zones. Outputs are estimates of direct business interruption loss for the region by industry, month (over the first year following the earthquake), and SCPM zone.

EPEDAT projects structure losses in the five-county Los Angeles metropolitan region of between $21.7 billion and $36.2 billion for the Elysian Park event. If building contents are included, property damage is estimated at $33.9 to $56.6 billion. Residential damage accounts for approximately two-thirds of the total. These estimates do not include damage to bridges or other infrastructure. About 72 percent of the structural damage to buildings is estimated to occur in Los Angeles County.

A corresponding change in final demand drives SCPM2, ultimately providing changes in output and employment for 17 sectors across 308 zones. This is an iterative calculation. Direct changes are exogenous, and already spatially identified. SCPM2 allocates indirect and induced changes in a way that respects both observed travel behavior and new network costs. A core contribution of this research is the ability to more completely endogenize submetropolitan freight and passengers flows and destinations. In this case, nine classes of passenger flows were combined with four classes of freight and loaded on a common network.

Bridge damage results were generated for 200 Monte Carlo simulations of the Elysian Park scenario earthquake. The bridge damage index achieved by any specific structure varies across each simulation, but each outcome is drawn from the fixed stochastic process corresponding to the Elysian Park scenario. Collectively, these simulations correspond to a distribution of damaged transportation networks. Each network is characterized (in part) by a vector of 2,810 bridges, each assigned a BDI value. The alternative bridge closure criteria (BDI > 0.30, BDI > 0.75) are applied to every bridge in every network in this set, producing two new distributions. The transportation networks in these distributions are still characterized by a vector of 2,810 bridges, but each bridge is now open (1), or closed (0).

Our model of the Los Angeles economy is convergent, but it is computationally infeasible to exhaustively investigate each network state represented in these distributions of damaged networks. Instead, we selected representative members of each distribution. The 200 simulations were rank ordered in terms of the baseline vehicle-miles that would otherwise be traveled across the damaged links. This rank ordering made it possible to identify those simulations that are:

- maximally disruptive with respect to baseline transportation flows; and
- representative in a median sense.

An example of preliminary simulation results describing the full costs of a magnitude 7.1 Elysian Park event are summarized in table 11.3. Row A reflects the midpoint of the range of structure damage predicted by EPEDAT, $45.25 billion, including $29 billion in structure loss. Row B is the sum of direct, indirect, and induced losses computed by the input-output model of the five-county, Los Angeles metropolitan area. This sum is $46.7 billion. These aggregate values are identical across all other simulations (Cho *et al.*, 1999). Row C summarizes the post earthquake network equilibrium transportation costs in light of reduced production and reduced network capacity. These values do vary across all simulations. Table 11.3 corresponds to median simulated disruption of baseline transportation combined with a risk tolerant bridge closure criteria that leaves moderately damaged structures open to normal traffic. In this case 122 of 16,946 network links are closed due to bridge damage. This loss of almost 480 lane miles results in a substantial retention of transportation network capacity, and a relatively small increase in transportation costs of almost $1.5 billion.

11.3 Bridge Reconstruction

The previous discussion extended our abilities to account for both the levels and spatially disaggregated nature of earthquake losses. The objective of our efforts is to support and improve pre- and post- earthquake policy decisions. Identification of efficient reconstruction strategies is an obvious post-earthquake objective.

11.3.1 Application of SCPM2 to the Evaluation of Bridge Reconstruction Strategies

There are numerous decisions that affect bridge repair costs. These include how damaged bridges are grouped to define repair projects, and associated equipment management, traffic diversion, and network delay costs.

Table 11.3 Total Loss ($Billions): Elysian Park Magnitude 7.1 Earthquake, Maximum Simulated Disruption to Baseline Transportation (Closure at Bridge Damage Index ≥ 0.75)

Loss Type	Baseline		Elysian Park Scenario: Risk Tolerant Bridge Closure Criterion	
A Structure Loss[a]			$ 45.250 billion (48.35% of total)	
Business Loss				
Direct Loss[b]			28.155	
Indirect Loss[c]			9.627	
Induced Loss[d]			8.955	
B Business Loss Subtotal			46.737 billion (49.95% of total)	
Network Costs[e]	PCU Minutes	$Billions	PCU Minutes	$Billions
Personal Travel Cost	85,396,813	21.290	89,945,131.	22.424
Freight Cost	10,298,781	4.550	10,966,123.	4.844
Total Travel Cost	95,695,594	25.839	100,911,255.	27.268
Network Loss = Δ Network Costs			PCU Minutes	$Billions
Δ Personal Travel Cost			4,548,318.	1.134
Δ Freight Cost			667,343.	0.295
C Δ Total Travel Cost			5,215,661.	1.429 (1.5% of total)
D Bridge Repair Cost (Excludes Delay Cost)			Median $Billions	Mean $Billions
			0.071	0.219
Loss Total = A + B + C +D			$ 93.487	$ 93.635

Notes: a. Midpoint EPEDAT outputs, EQE International.
b. EPEDAT, EQE International.
c. Regional Science Research Institute PC-IO (RSRI) Model for the Los Angeles Metropolitan Area.
d. Difference between the RSRI solution with the processing sector closed with respect to labor and the RSRI solution with the processing sector open with respect to labor.
e. Network cost is the generalized total transportation cost associated with a simultaneous equilibrium across choice of destinations and routes. These estimates reflect 365 travel days per year, an average vehicle occupancy of 1.42 for passenger cars, 2.14 passenger car units per truck, a value of time for individuals of $6.5/hour, and $35/hr for freight.

Row D in table 11.3 includes preliminary bridge repair cost estimates based on a discriminant analysis of Loma Prieta and Northridge Earthquake bridge damage states and estimated repair costs. Mean and median repair costs are reported. The full costs of the earthquake are estimated to be almost $93.5 billion, close to 14 percent of the SCAG area's 1990 GRP, although direct (business interruption) costs account for about seven percent. In this case, transportation costs account for a small share of the full cost of the earthquake. However, these costs include an optimistic assumption: None of the damaged bridges left open to traffic ever collapse.

The loss-of-function curves utilized in this research describe production capacity over a one-year period following the earthquake. Production capacity was predicted to approach pre-earthquake levels within six months. Restoration of transportation network capacity is less rapid.[1] Bridges were assumed to remain closed for one year following the earthquake. During this period they are repaired or replaced. Other assumptions or empirical relationships can certainly be accommodated to further refine these preliminary results. State DOT officials provided very different expert estimates of the time required for repair following extensive damage.

SCPM2 provides unprecedented disaggregation of economic impacts over metropolitan space. Employment and production losses are calculated at the level of 1,527 traffic analysis zones, and the aggregated for 310 cities and communities, which together exhaust the urbanized portions of the Los Angeles five-county metropolitan area. More complete tabular results, maps, and narrative summaries for this element of the research are available on our website (www.usc.edu/schools/sppd).

Corresponding results were calculated for other representative bridge-closure simulations. All of these results included the change in network costs associated with reductions in supply of transportation services. The resulting redistribution of economic activities are just one source of local (city level) losses. Increases in network transportation costs are another significant source of local impacts. These costs are more difficult to disaggregate. There is insufficient information to reliably allocate these transportation costs to economic sectors, but these costs can be geographically distributed to traffic origins and destinations.

These new network costs may also influence the distribution of indirect and induced economic losses via the distance decay relationship between travel cost and destination choice. But in all our simulations, the overall GRP changes associated with indirect and induced economic losses remain modest. Differences in spatially distributed impacts are also modest.

The Southern California region has a highly redundant road and highway system, and these findings corroborate the economic importance of the regional transportation network's high levels of redundancy. The high level of travel endogeneity associated with the travel choices represented in SCPM2 is explained by the redundancy of the Los Angeles regional transportation network. The various bridge closure simulations affect between 84 and 326 directional network links, including freeway and arterial links. The representation of the network contained in SCPM2 includes 16,946 links. Bridge closures do impact total travel cost and route choice. A comparison of our simulations indicated that the cumulative value of increased network cost can be significant, but the day-to-day increase does not induce profound changes in destination choice, and thus does not have a pronounced impact on the spatial distribution of economic losses.

These results suggest several hypotheses relating to the relationships accounted for by SCPM2 and the way these relationships are parameterized.

- This application of SCPM2 remains incomplete. The loss-of-function curves apply only to production activities. The impact on households, *i.e.*, on the production of labor, has not yet been accounted for, and changes in the spatial

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[1] All SCPM2 outputs are for one-year periods. Outputs for shorter intervals are scaled proportionately.

distribution of activities and losses do not reflect the impact of changes in household consumption.

- Destination choice may be more sensitive to post-earthquake travel costs than to pre-earthquake costs. The distance decay functions in SCPM2 are estimated with pre-earthquake data. Post earthquake responses to travel cost may be different. Travelers may be more risk averse than the distance decay functions in SCPM2 imply.
- Travelers may also diminish trip frequencies in response to the cost of travel. In SCPM2, demand for freight transportation changes as a result of the earthquake, but passenger trip generation rates remain unchanged. If trip generation rates are endogenized, some longer passenger trips would be removed from these results, and this would intensify changes in the geographic distribution of activities and losses. However, these two latter limitations of earlier versions of SCPM2 have been remedied in Section IV below.

We can execute this procedure for any relevant earthquake, mitigation, or reconstruction scenario. The baseline exercise describes pre-earthquake conditions. The simulations described above summarize post-earthquake outcomes conditioned on present levels of mitigation. These results can be contrasted with results that include mitigation measures. The difference between these full-cost results measures the benefits of the mitigation, to be compared against the costs of implementing the mitigation. Importantly, the benefits measured in this manner are provided at the local submetropolitan level. This includes municipalities, and in the case of the City of Los Angeles, Council districts. If all politics are indeed local, then results like this are critically important to policy implementation.

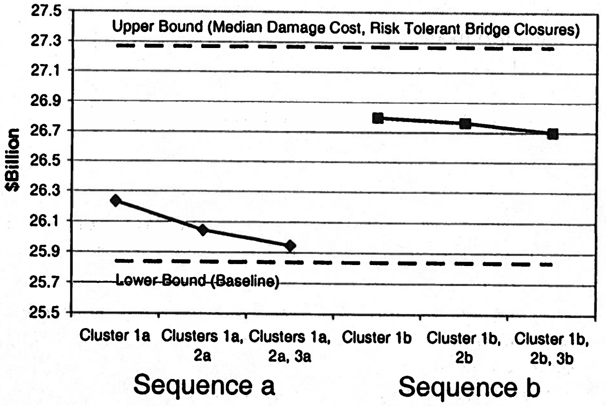

Figure 11.5 Transportation Network Costs of Two Alternative Cluster Repair Sequences (Cho *et al.*, 2000)

There is considerable interest in efficient bridge reconstruction approaches. SCPM2 is well suited to comparing the economic benefits of alternative schemes. Figure 11.5 summarizes the results of some preliminary simulations. These include the following sequence of steps:

- Identify spatial clusters of bridges. The highway agency is likely to want to repair bridges in groups that are spatially proximate. This reduces equipment staging and project set-up costs. Our procedure used a traveling salesman algorithm to identify eight spatial clusters of damaged links. This is one of several alternative clustering algorithms that can be applied. Our preliminary effort does not address improving these initial clusters, but this is a reasonable extension.
- Calculate the total pre-event traffic link volumes associated with each cluster. This is a simple measure of the importance of the facilities in each cluster. More sophisticated alternatives that account more carefully for changes in post event flows are available.
- Select an efficient sequence of bridge repairs. This selection algorithm may be either heuristic or an optimum-seeking dynamic program (Kiyota, Vandebona, and Tauoue, 1999).
- Estimate network cost improvements as cluster repair benefits associated with the repair sequence.

In an optimization exercise, the last two steps would likely be combined. These steps could be separate in some heuristic procedures. In preliminary work, we selected a cluster repair sequence based on the pre-event traffic volumes for the cluster. The highest-volume cluster was repaired first, followed by the next-highest volume cluster, etc. The magnitudes of network cost reductions are plotted in figure 11.5. System improvements are measured in terms of post-repair network flows. These benefits should be compared to the bridge reconstruction costs in row D of table 11.3.

The lower bound in figure 11.5 describes the network user costs on an undamaged network, $25.839 billion (see table 11.3). The upper bound is network costs given median damage (200 simulations) associated with the Elysian Park scenario, and a risk-tolerant bridge closure policy that leaves moderately damaged bridges open to traffic.

The lower left-hand curve shows the network cost improvements associated with repairing the clusters in order of their total pre-event link volumes, starting with the highest volume cluster. The upper right-hand curve reverses this sequence, repairing the lowest volume cluster first. The plots have the expected shapes. In the lower-left, benefits from repairing additional clusters of bridges become available in ever smaller increments. In the case of the upper right curve, benefits become available in ever larger increments.

11.3.2 Discussion

Our integration of seismic, transportation network, spatial allocation, and input-output models permits the study of how the economic impacts of industrial and transportation structure loss are distributed over metropolitan space. Some of this loss is produced directly by the earthquake, which destroys industrial capacity. The procedure accounts for the impact of industrial structure losses and resulting direct production losses. The model computes further indirect and induced losses, and makes the spatial distribution of these losses sensitive to increases in network costs resulting from transportation structure losses.

These preliminary research results permit us to address the problem of bridge reconstruction prioritization. To do so, we first assess the earthquake risk to the transportation system and the urban economy by accounting for a wide range of outcomes associated with damage to bridges and production facilities. The costs of efficient bridge reconstruction improve the accounting of the costs of the earthquake. This approach has four elements, specifying an integrated model, assembling data from disparate sources, achieving computability, and identifying bridge reconstruction strategies.

While these results are preliminary, they demonstrate the way SCPM2 can be applied. We are currently testing alternate bridge repair sequences and plan to compare these with actual experience from the Kobe and Northridge bridge repair efforts.

11.4 SCPM2 Extensions: Endogenizing Work and Shopping Trip Attractions and Productions

In SCPM2, all distance-decay functions were endogenously determined (Cho *et al.*, 2001). In light of severe shocks to network capacity and also to the demand for network services, this seemed to be a necessary step in developing an integrated model.

Yet, it can also be argued that passenger trip generation characteristics would change in response to shocks of this nature. In the applications that follow, we modified SCPM2 to account for some of these effects. We endogenized trip attractions and productions for work trips and for shopping trips. The following four extensions implement these changes. The resulting elaboration of SCPM2 is convergent.

Zone specific economic impacts will produce changes in work trips attracted to each zone. Direct job impacts V_d^z are given by zone. However, total impacts also include indirect impacts V_n^z and induced impacts V_u^z. These indirect and induced estimates are model outputs. The requirement that trips attracted match trips produced implies a corresponding change in work trip productions. The objective is to predict mutually consistent changes in work trip ends and economic impacts. Define the change in work trips attracted to zone z to be:

$$dA_{w,i+1}^z = \rho \cdot \sum_k \left(V_{d,k,i}^z + V_{n,k,i}^z + V_{u,k,i}^z \right) \tag{11.4}$$

where ρ = a constant that converts economic impacts to trip changes,
i.e., a ratio of the total number of trips / total regional output,
k = an industrial sector index, and
i = an iteration counter.

Changes in work trips produced in and attracted to each zone should be consistent with SCPM2's journey-from-home-to-work (*JHW*) matrix. This *JHW* matrix gives the proportion of work trips terminating in each zone for each origin. Balancing work trip productions and attractions requires that:

$$\begin{aligned} dP_{w,i}^z &= P_{w,i}^z - JHW \cdot \left(A_{w,i}^z + dA_{w,i}^z \right) = \\ &= P_{w,i}^z - JHW \cdot \left(A_{w,i+1}^z \right) \end{aligned} \tag{11.5}$$

Reductions in work trips and employment reduce aggregate household income in each zone. This reduces shopping trips produced in each zone. Define the change in shopping trips produced in zone z to be dP_s^z. Fewer shopping trips will occur, but assume expenditures per shopping trip do not change. If the income-driven change in shopping trip productions is proportional to the change in work trip productions, then:

$$P_{s,i+1}^z = P_{s,i}^z \cdot \left[\frac{P_{w,i}^z + dP_{w,i}^z}{P_{w,i}^z} \right] = P_{s,i}^z \cdot \left[\frac{P_{w,i+1}^z}{P_{w,i}^z} \right] \tag{11.6}$$

Reduced zonal retail and service sector activity reduces the number of shopping trips attracted to each zone. Define the change in shopping trips attracted to zone z to be dA_s^z. $X_{retail,i}^z$ and $X_{service,i}^z$ are total retail and service activity calculated at iteration i, respectively. Total baseline retail and service output are the initial values. Changes in retail and service activities result from direct, indirect, and induced impacts on those economic sectors. That is:

$$dX_{retail,i}^z = V_{d,retail,i}^z + V_{n,retail,i}^z + V_{u,retail,i}^z \tag{11.7.a}$$

And:

$$dX_{service,i}^z = V_{d,service,i}^z + V_{n,service,i}^z + V_{u,service,i}^z \tag{11.7.b}$$

These zone specific changes in retail and service activities produce changes in the shopping trips attracted to each zone:

$$\begin{aligned} A_{s,i+1}^z &= A_{s,i}^z \cdot \left[\frac{\left(X_{retail,i}^z + X_{service,i}^z \right) - \left(dX_{retail,i}^z + dX_{service,i}^z \right)}{X_{retail,i}^z + X_{service,i}^z} \right] = \\ &= A_{s,i}^z \cdot \left[\frac{X_{retail,i+1}^z + X_{service,i+1}^z}{X_{retail,i}^z + X_{service,i}^z} \right] \end{aligned} \tag{11.8}$$

This procedure modifies the outer iteration loop identified in the lower portion of figure 11.1. This extension is convergent. This iterative procedure terminates when the changes in total trip productions and attractions become relatively small. As generalized travel costs stabilize across SCPM2 iterations, total trip productions and attractions stabilize. This simultaneously defines the trip matrices (OD requirements) generated in SCPM2's inner loop, and zone specific economic impacts defined in the outer loop of figure 11.1.

We have applied the approach described in equations (11.4) through (11.8) to the problem of endogenizing shopping trip ends. Results follow below. Reductions were calculated for both working and shopping trips, but only the changes in shopping trip requirements were imposed on the network equilibrium model and generalized cost calculations. An argument can be mounted for reducing both shopping and work trips, but shopping trips are certainly the more discretionary of the two.

Table 11.4 summarizes transportation network cost results for several representative bridge damage and policy scenarios. As before, scenarios are defined in terms of bridge damage, bridge closure policies, and the pre-earthquake traffic volumes on links affected by bridge closures. In the maximum scenario, the sum of affected baseline link traffic volumes is a maximum from a set 200 Monte Carlo realizations of earthquake damage. The median scenario is the scenario that provides the median affected total traffic volume. Recall that bridge damage is expressed in terms of a bridge damage index that ranges from 0 (no damage) to 1 (collapse). Closing only severely damaged bridges, *i.e.*, BDI ≥ 0.75, is a risk tolerant policy. Row 5 in each table modifies the results from row 1 by adding the effects of shopping trip end adjustments. These adjustments greatly reduce the demand for transportation, and thus associated flows and delays. This more meaningfully models the expected level of service on the network, but no attempt has been made to account for the economic value of these missing trips. The nature of earthquake-induced adjustments in work trip ends remains an important research question.

11.5 Application of SCPM2 to the Determination of Bridge Reconstruction Costs

11.5.1 Price Effects, Bottlenecks, and Budget Forecasts

Large-scale reconstruction efforts such as those identified above produce a variety of economic impacts. These include substantial indirect and induced production activities prompted throughout the metropolitan economy, as well as related price effects. It is important to anticipate these price effects as best we can because price increases intensify pressure on reconstruction budgets. Most important, local increases in wages augment reconstruction budget requirements. Additional system-wide price effects follow from the additional earnings accruing to households. SCPM2 is applied iteratively in the manner shown below to determine the size and location of all reconstruction employment and income effects. We do this for bridge repair budgets determined above, which we now augment by the price effects that the model computes.

11.5.2 Determining Reconstruction Budgets with Endogenous Price Adjustments

Linear interindustry models have been elaborated in many ways (Miller and Blair, 1985). In what follows, we describe how we utilized some of the elaborated models to endogenize price effects. Some of the critical baseline data are from the 1993 PC-IO package from the Regional Science Research Institute. These data includes X_0, a vector of baseline total outputs for the region; and A, a matrix of technical coefficients for the regional economy. Line D in table 11.3 provides an initial estimate of bridge reconstruction and repair costs. These are merely direct costs, and are likely to cause substantial multiplier effects.

Table 11.4 Total Travel Cost (before repairs) by Earthquake Scenario (Passenger Car Units × Minutes)

Total Travel Cost (before bridge repairs) by Earthquake Scenario (Passenger Car Units × Minutes)	Driver Delay	Freight Delay	Total Delay
Baseline	85,396,813	10,298,781	95,695,594
Close if BDI ≥ 0.30, Maximum Scenario	225,830,486	28,285,954	254,116,440
Close if BDI ≥ 0.30, Median Scenario	117,493,842	15,602,872	133,096,713
Close if BDI ≥ 0.75, Maximum Scenario	94,349,424	11,581,677	105,931,101
Close if BDI ≥ 0.75, Median Scenario	89,945,131	10,966,123	100,911,255
Close if BDI ≥ 0.30, Maximum Scenario with Trip End Adjustments	90,175,132	10,483,089	100,658,221
Total Travel Cost (before bridge repairs) by Earthquake Scenario ($Billions)	Driver Delay	Freight Delay	Total Delay
Baseline	21.290	4.550	25.839
Close if BDI ≥ 0.30, Maximum Scenario	56.300	12.495	68.795
Close if BDI ≥ 0.30, Median Scenario	29.291	6.893	36.184
Close if BDI ≥ 0.75, Maximum Scenario	23.522	5.116	28.638
Close if BDI ≥ 0.75, Median Scenario	22.424	4.844	27.268
Close if BDI ≥ 0.30, Maximum Scenario with Trip End Adjustments	22.481	4.631	27.112
Changes in Total Travel Cost Relative to Baseline (before bridge repairs) by Earthquake Scenarios (PCU × Minutes)	Driver Delay	Freight Delay	Total Delay
Close if BDI ≥ 0.30, Maximum Scenario	140,433,673	17,987,173	158,420,846
Close if BDI ≥ 0.30, Median Scenario	32,097,029	5,304,091	37,401,119
Close if BDI ≥ 0.75, Maximum Scenario	8,952,611	1,282,896	10,235,507
Close if BDI ≥ 0.75, Median Scenario	4,548,318	667,343	5,215,661
Close if BDI ≥ 0.30, Maximum Scenario with Trip End Adjustments	4,778,318	184,309	4,962,627
Changes in Total Travel Cost Relative to Baseline (before repairs) by Earthquake Scenarios ($Billions)	Driver Delay	Freight Delay	Total Delay
Close if BDI ≥ 0.30, Maximum Scenario	35.010	7.946	42.956
Close if BDI ≥ 0.30, Median Scenario	8.002	2.343	10.345
Close if BDI ≥ 0.75, Maximum Scenario	2.232	0.567	2.799
Close if BDI ≥ 0.75, Median Scenario	1.134	0.295	1.429
Close if BDI ≥ 0.30, Maximum Scenario with Trip End Adjustments	1.191	0.081	1.273

Notes: BDI = Bridge Damage Index. Closing a link for which BDI ≥ 0.30 is risk averse. Closing a link for which BDI ≥ 0.75 is risk tolerant.

Various economic translators are published by the Regional Science Research Institute. These translators are generic final demand vectors calibrated to unit expenditures on various kinds of projects. Each kind of project is defined by the mix of inputs required. RSRI translator #37 specifies plausible proportions of expenditures corresponding to the final demand sectors involved with bridge and highway construction. Application of these allows any project budget to be decomposed into a vector of final demands. Analysts can then use the IO model to calculate the full economic impacts of any major construction project. Our extension of this standard procedure is to calculate price effects that can be expected when project budgets become large.

Using standard input-output notation, the calculation procedure is as follows. Run the version of the I-O model that is closed with respect to the household sector. This gives:

$$dX_{i=0} = (I - A)^{-1} \cdot dY_{i=0} \tag{11.9}$$

where dY_0 = change in direct demand associated with bridge construction;
dX_0 = the associated change in total output; and
i = an iteration counter.

Concurrent with this result, there is a vector of household income changes, dW_0, as a result of the reconstruction program. We address the difficult problem of evaluating labor supply elasticity effects by adoption of an overtime rate. The burden of bridge reconstruction would require additional labor inputs to expedite rebuilding the bridges within a reasonable time period. If the construction sector were close to full employment, this could require attracting construction workers from outside the region. Such workers would have to be offered higher wages to pull them in and to affect what in some cases would be short-term (*e.g.* less than a year) local subsistence costs. Laub (1993) uses the example of Florida's Hurricane Andrew in 1992, to make the case that price increases, particularly with respect to labor, are highly likely following a natural disaster; and in fact, necessary to attract the materials and services needed for rapid recovery. But would any of these wage premia spillover into the wages received by local workers? To avoid having to address this difficult question, an alternative solution was adopted. Instead of attracting more workers from outside, the existing construction labor force could be used more intensively by allowing enough overtime to accommodate the additional labor requirements for bridge construction. The additional labor costs and associated price effects would not necessarily be the same as those resulting from offering higher wages to workers from outside the region, but they offer an acceptable alternative estimate.

Assuming a 24-hour, seven-day weekly work schedule, and a 50 percent wage premium for all overtime work, the average wage premium is 38 percent. Applying this assumed overtime rate to the construction sector:

$$dW^c_{i=0} = dW^c \cdot 0.38 \tag{11.10}$$

where dW^c is the change in labor cost in construction sectors. Thus the revised budget, including labor overtime costs, is:

$$dY_{i=1} = dY_{i=0} + dW^c_{i=0} \tag{11.11}$$

In addition we account for the impact of price effects on final demand. These price effects are calculated via the following iterative procedure. Given the revised budget from equation (11.11), run the closed IO model to obtain

$$dX_{i=1} = (I - A)^{-1} \cdot dY_{i=1} \tag{11.12}$$

Equation (11.12) updates the values of $dX_{i=0}$ obtained in equation (11.9). The household row of the transactions table gives $dW_{i=1}$, an initial vector of wage changes in all sectors. Higher wages in the system mean higher prices. Initial changes in wages are used to generate an initial estimate of changes in prices:

$$dP_{i=1} = (I - A^T)^{-1} \cdot \frac{dW_{i=1}}{X_0} \tag{11.13}$$

These higher prices further increase the required reconstruction budget:

$$dY_{i+1} = dY_i \cdot (1 - dP_i)^{-1} \tag{11.14}$$

The feedback between reconstruction budget requirements and prices described by equations (11.12) through (11.14) eventually attenuates, when the quantity $dP_{i+1} - dP_i$ is sufficiently small. A summary of this iterative procedure appears in figure 11.4.

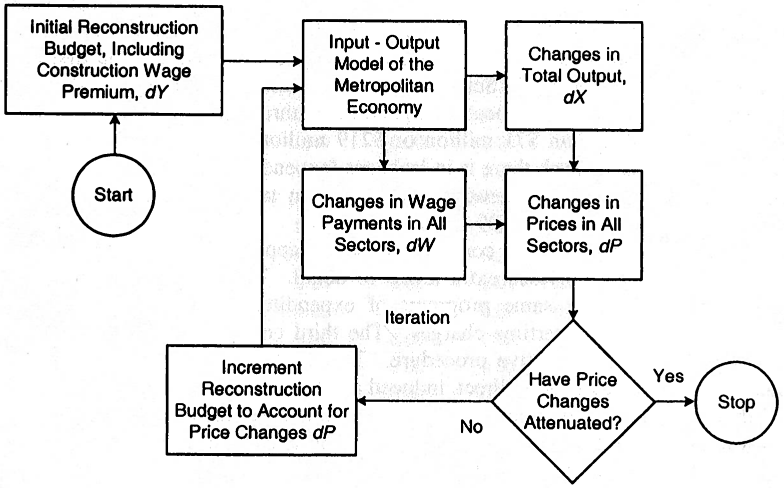

Figure 11.4 Computing a Reconstruction Budget that Accounts for Exogenous Price Effects

11.5.3 Simulation Results for Bridge Reconstruction with Endogenous Price Effects

We apply mean and median reconstruction cost alternatives to one of the risk tolerant bridge closure scenario (DS = 0.75, median traffic disruption). Table 11.5 summarizes the damage associated with this scenario, and associated mean and median facility repair costs. The cost distribution is skewed, and mean costs are more than twice median costs. As noted above, bridge repair cost estimates are based on a discriminant analysis of Loma Prieta and Northridge Earthquake bridge damage states and estimated repair costs.

Table 11.5 Bridge Damage Data

Bridge Damage State	Collapsed	Major	Moderate	Minor	Total
Number of Bridges	3	43	120	67	233
Median Repair Cost/Bridge ($1,000)	17,260	362	28	11	
Mean Repair Cost/Bridge ($1,000)	47,274	1,278	138	89	
Total Repair Cost ($1,000)					
Median Scenario	51,780	15,555	3,337	707	71,379
Mean Scenario	141,823	54,962	16,541	5,992	219,317

Applying this procedure for the median and mean bridge repair costs generates the results in tables 11.6 and 11.7, respectively. Each of the two tables show model IO results for the various modeling steps described immediately above. The first column describes how the Regional Science Research Institute's bridge and highway construction translator #37 allocates expenditures throughout the construction and other sectors. Rather than $71 million or $219 million spent within the region, the model determines how much there is in leakages (expenditures that accrue to firms and workers residing outside the metropolitan area). In table 11.6, leakages are $9.62 million. In table 11.7, they are $29.67 million.

We have disaggregated the construction sector appearing in the 17-sector model because the translator provides extra levels of detail. The second columns in tables 11.6 and 11.7 show the same programs of expenditure if the contracting agency absorbs the 38 percent overtime charges. The third columns show the same budget after completion of the iterative procedure. This is the new vector of direct effects (column 4), used to calculate indirect, induced and total effects (columns 5, 6, and 7).

Table 11.8 details the additional transportation costs incurred in the process of reconstruction. Table 11.9 contrasts the mean and median reconstruction cost outcomes relative to the baseline described in table 11.3. Accounting for endogenous price effects increases mean reconstruction budget requirements by approximately $42 million. This assumes bridges are reconstructed at the mean cost observed in the data.

Table 11.6 Reconstruction Budget and Interindustry Economic Effects of Median Cost[a] Reconstruction Activity

	Reconstruction Budget[b]			Economic Effects of Reconstruction[b]			
Sector	Initial Budget	Budget With Overtime[c]	New Budget Considering Price Effects	Direct	Indirect	Induced	Total
1. Agriculture	0.00	0.00	0.00	0.00	0.08	0.29	0.37
2. Mining	0.46	0.46	0.46	0.46	0.21	0.30	0.97
3. Construction	38.01	49.00	49.28	49.28	0.50	0.62	50.40
32. general const. contractors	4.39	5.65	5.66	5.66	0.07	0.09	5.82
33. highway & street construction	3.14	3.92	3.95	3.95	0.00	0.00	3.95
34. other heavy const. contractors	9.41	11.96	12.07	12.07	0.02	0.03	12.11
35. plumb/heat/air cond. contrctrs	1.66	2.17	2.17	2.17	0.03	0.04	2.23
36. painting, papering, decorating	0.00	0.01	0.01	0.01	0.01	0.01	0.03
37. electrical const. contractors	6.10	8.02	8.05	8.05	0.03	0.05	8.13
38. masonry, drywall & plastering	2.22	2.88	2.89	2.89	0.03	0.03	2.95
39. carpentering & flooring	0.00	0.01	0.01	0.01	0.01	0.01	0.03
40. roofing & sheet metal work	0.00	0.01	0.01	0.01	0.01	0.02	0.03
41. concrete work	1.11	1.44	1.44	1.44	0.01	0.02	1.47
42. water well drilling	0.00	0.00	0.00	0.00	0.00	0.00	0.00
43. special trade contractors, nec	9.98	12.95	13.04	13.04	0.02	0.03	13.09
44. maint & rep: residential bldgs	0.00	0.00	0.00	0.00	0.02	0.10	0.12
45. maint & rep: non-res. bldgs.	0.00	0.00	0.00	0.00	0.23	0.16	0.39
46. maint & rep: farm residences	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47. maint & rep: other farm bldgs.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
58. maint & rep: streets & h'ways	0.00	0.00	0.00	0.00	0.00	0.00	0.00
59. maint & rep: petr. & gas wells	0.00	0.00	0.00	0.00	0.01	0.01	0.02
60. maint & rep: other nonbldg fac	0.00	0.00	0.00	0.00	0.01	0.01	0.02
4. Manufacturing (nondurable)	1.71	1.71	1.71	1.71	1.82	5.94	9.47
5. Manufacturing (durable)	14.57	14.57	14.57	14.57	3.73	2.21	20.50
6. Transportation	0.87	0.87	0.87	0.87	0.54	0.47	1.87
7. Communications and utilities	0.22	0.22	0.22	0.22	0.71	2.15	3.09
8. Wholesale trade	2.02	2.02	2.02	2.02	1.90	1.77	5.68
9. Retail	0.00	0.00	0.00	0.00	1.44	6.48	7.92
10. F.I.R.E.	0.00	0.00	0.00	0.00	1.76	9.69	11.45
11. Business services	0.00	0.00	0.00	0.00	2.71	2.19	4.90
12. Personal services	0.00	0.00	0.00	0.00	0.19	0.80	0.99
13. Entertainment and recreation	0.00	0.00	0.00	0.00	0.05	0.86	0.91
14. Health	0.00	0.00	0.00	0.00	0.00	0.80	0.80
15. Educational services	0.00	0.00	0.00	0.00	0.01	0.61	0.62
16. Professional and related	3.52	3.52	3.52	3.52	1.13	2.59	7.23
17. Government	0.00	0.00	0.00	0.00	0.26	1.04	1.30
Sum	61.38	72.37	72.65	72.65	17.03	38.80	128.48
Leakage	9.62		11.39				
Total	71.00		84.04				

Notes: a. Median total bridge repair/replacement cost = $71 Million.
b. $Millions.
c. Prime Rate for Overtime-Labor in Construction Sector = [40+(128 × 1.5)]/168=1.38.

Table 11.7 Reconstruction Budget and Interindustry Economic Effects of Mean[a] Cost Reconstruction Activity

Sector	Reconstruction Budget[b] Initial Budget	Budget With Overtime[c]	New Budget Considering Price Effects	Economic Effects of Reconstruction[b] Direct	Indirect	Induced	Total
1. Agriculture	0.00	0.00	0.00	0.00	0.25	0.90	1.15
2. Mining	1.43	1.43	1.43	1.43	0.63	0.95	3.01
3. Construction	117.25	151.14	153.88	153.88	1.56	1.92	157.36
32. general const. contractors	13.54	17.42	17.49	17.49	0.23	0.28	18.00
33. highway & street construction	9.67	12.08	12.39	12.39	0.00	0.01	12.41
34. other heavy const. contractors	29.02	36.90	37.93	37.93	0.05	0.08	38.06
35. plumb/heat/air cond. contrctrs	5.12	6.68	6.71	6.71	0.08	0.12	6.91
36. painting, papering, decorating	0.00	0.02	0.02	0.02	0.03	0.04	0.08
37. electrical const. contractors	18.82	24.72	25.07	25.07	0.09	0.15	25.31
38. masonry, drywall & plastering	6.85	8.89	8.96	8.96	0.08	0.11	9.14
39. carpentering & flooring	0.00	0.02	0.02	0.02	0.03	0.04	0.09
40. roofing & sheet metal work	0.00	0.02	0.02	0.02	0.03	0.05	0.10
41. concrete work	3.42	4.44	4.47	4.47	0.03	0.05	4.45
42. water well drilling	0.00	0.00	0.00	0.00	0.00	0.01	0.01
43. special trade contractors, nec	30.80	39.93	40.80	40.80	0.05	0.11	40.97
44. maint & rep: residential bldgs	0.00	0.00	0.00	0.00	0.06	0.32	0.38
45. maint & rep: non-res. bldgs.	0.00	0.00	0.00	0.00	0.72	0.49	1.21
46. maint & rep: farm residences	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47. maint & rep: other farm bldgs.	0.00	0.00	0.00	0.00	0.00	0.01	0.01
58. maint & rep: streets & h'ways	0.00	0.00	0.00	0.00	0.00	0.01	0.01
59. maint & rep: petr. & gas wells	0.00	0.00	0.00	0.00	0.04	0.02	0.06
60. maint & rep: other nonbldg fac	0.00	0.00	0.00	0.00	0.02	0.03	0.05
4. Manufacturing (nondurable)	5.28	5.28	5.28	5.28	5.63	18.51	29.42
5. Manufacturing (durable)	44.93	44.93	44.95	44.95	11.52	6.88	63.35
6. Transportation	2.68	2.68	2.68	2.68	1.66	1.45	5.79
7. Communications and utilities	0.69	0.69	0.69	0.69	2.21	6.70	9.60
8. Wholesale trade	6.22	6.22	6.22	6.22	5.89	5.50	17.60
9. Retail	0.00	0.00	0.00	0.00	4.47	20.19	24.66
10. F.I.R.E.	0.00	0.00	0.00	0.00	5.46	30.18	35.64
11. Business services	0.00	0.00	0.00	0.00	8.43	6.81	15.24
12. Personal services	0.00	0.00	0.00	0.00	0.58	2.50	3.08
13. Entertainment and recreation	0.00	0.00	0.00	0.00	0.16	2.69	2.84
14. Health	0.00	0.00	0.00	0.00	0.01	2.48	2.49
15. Educational services	0.00	0.00	0.00	0.00	0.03	1.90	1.93
16. Professional and related	10.86	10.86	10.86	10.86	3.49	8.06	22.41
17. Government	0.00	0.00	0.00	0.00	0.82	3.23	4.06
Sum	189.33	223.22	225.99	225.99	52.80	120.86	399.65
Leakage	29.67		35.42				
Total	219.00		261.41				

Notes: a. Mean total bridge repair/replacement cost = $219 Million.
b. $Millions.
c. Prime Rate for Overtime-Labor in Construction Sector = [40+(128 × 1.5)]/168=1.38.

Table 11.8 Additional Travel Cost Associated with Mean and Median Reconstruction Activities

Median Reconstruction Cost Scenario	Passenger Delay	Freight Delay	Total Delay
Total Travel Cost (Baseline Flows + Reconstruction Flows)			
(PCU × Minutes)	91,702,850	11,070,634	102,773,483
($Billion)	22.862	4.890	27.752
Change Due to Reconstruction Flows			
(PCU × Minutes)	1,757,719	104,511	1,862,228
($Billion)	0.438	0.046	0.484

Mean Reconstruction Cost Scenario	Passenger Delay	Freight Delay	Total Delay
Total Travel Cost (Baseline Flows + Reconstruction Flows)			
(PCU × Minutes)	92,349,189	11,110,640	103,459,830
($Billion)	23.023	4.908	27.931
Change Due to Reconstruction Flows			
(PCU × Minutes)	2,404,058	144,517	2,548,575
($Billion)	0.599	0.064	0.663

Table 11.9 Bridge Reconstruction Cost Summary ($Billions)

	Bridge Repair Costs Ignoring Endogenous Price Effects[a]	Accounting for Endogenous Price Effects	Additional Travel Cost Associated with Reconstruction[b]
Median Reconstruction Cost Scenario	$ 0.071	$ 0.084	0.484
Mean Reconstruction Cost Scenario	$ 0.219	$ 0.261[b]	0.663

Notes: a. Table 11.3.
b. Table 11.8.

11.6 Conclusions

This chapter addresses some often ignored repercussions of a major earthquake by supplementing the standard structural damage impacts with business loss effects (although these have been a few studies of this issue) and disruptions to the transportation network. These include increased freight and travel costs resulting from damage to the network, and the supply inelasticities associated with a major bridge reconstruction effort. The goal of this effort is a full-cost approach to measuring earthquake impacts, but in fact the estimates derived here ($94.34 billion) are loose lower bounds. There are several reasons. First, the increase in travel costs in the post-earthquake situation is minimized by adopting a risk tolerant response to bridge damage. Only those facilities for which the bridge damage index exceeds 0.75 are closed. If the more conservative threshold (BDI ≥ 0.30) had been adopted, the median case travel costs increase would have surged to $10 billion. Second, the research does not include all costs inflicted on households. This study accounts only for residential structure damage and increased personal travel costs because of the damaged network. Dislocation costs if households have to move to temporary accommodation are ignored, as are possible reductions in consumption because the difficulty of getting to destinations. Third, there is no attention given in this research to the costs of possible deaths and injuries associated with an earthquake of this magnitude. Of course, such estimates would be contingent upon a number of unknowns, such as the time of day when the earthquake occurred. When all these considerations are taken into account, the full-costs of the earthquake would certainly be much higher.

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12 Analysis of Economic Impacts of an Earthquake on Transportation Network[*]

Jungyul Sohn,[1] Geoffrey J.D. Hewings,[2] Tschangho John Kim,[3] Jong Sung Lee,[3] and Sung-Gheel Jang[3]

[1] National Center for Smart Growth Research and Education, University of Maryland, and Regional Economics Applications Laboratory, University of Illinois, USA
e-mail: jsohn@umd.edu
[2] Regional Economics Applications Laboratory, University of Illinois, USA
e-mail: hewings@uiuc.edu
[3] Department of Urban and Regional Planning, University of Illinois, USA
e-mail: tjohnkim@uiuc.edu, jonglee1@uiuc.edu, sjang3@uiuc.edu

12.1 Introduction

Prior to the 1990s, natural disasters and their economic impacts were not a major field of study for regional economic analysts even though there was a sizeable literature based on structural engineering and geotechnical approaches. The latter approaches attempted to understand the behavior of earthquakes and to explore ways to prevent or minimize damage from the disaster should it occur. However, when decisions needs to be made on the retrofit of existing facilities as a prevention or the restoration of disrupted facilities after damages, economic considerations related to budgeting priorities have not been prominently featured. As a consequence, decisions about retrofit strategies tend to focus on engineering-based criteria (for example, bridge 21 on route 50 should be retrofitted because it presents the greatest probability of collapsing given an earthquake of magnitude x) rather than on economic criteria (for example, a 10% loss of capacity on bridge 10 on route 60 would create the greatest economic disruption under a similar earthquake scenario and hence would have the highest priority for retrofit). Hence, there is a clear need to provide some interface to explore the ways in which engineering-based assessments can be compared with those based on economic analysis tools. The current research described in this chapter provides such an interdisciplinary research effort.[1]

The purpose of the present research is to explore various economic impacts of the earthquake especially on the transportation network and to provide essential information for a rational retrofit strategy of this transportation network. The analysis is timely in that most other analyses have focused on disruption of economic facilities such as factories and offices, but have tended to ignore a strategic approach to transportation facilities. For the purpose of the research, a 25-year span of the final demand vectors are estimated as the reference values starting from the year 1993, the

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[1] For example, some of the functions in the scenario analysis come from the civil engineering research groups in the Mid-America Earthquake Center (MAEC).