EARTHQUAKE DISASTER MITIGATION FOR URBAN TRANSPORTATION SYSTEMS: AN INTEGRATED METHODOLOGY THAT BUILDS ON THE KOBE AND NORTHRIDGE EXPERIENCES

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ABSTRACT

Policy makers interested in evaluating the costs and benefits of earthquake retrofit and reconstruction strategies require a way to measure the benefits (costs avoided) of competing proposals. This requires an integrated, operational model of losses because of earthquake impacts on transportation and industrial capacity, and how these losses affect the metropolitan economy. This research examines several dimensions in the search for a "full-cost" measure of the economic impact of a 7.1 Elysian Park earthquake: structural damage, business interruptions, the effects of network disruption (increased travel costs and changes in trip behavior), and bridge repair costs (including supply-related additional labor inputs and endogenous price effects).

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I. INTRODUCTION

A. 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 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.

B. 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 economics (usually input-output 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.

II. SOUTHERN CALIFORNIA PLANNING MODEL 2 (SCPM2)[1]

A. 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 (Fang, et al 1998).

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.

Richardson's, et al (1993) Southern California Planning Model-1 (SCPM1), 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.

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.

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[1] Parts of Section II appear in Cho, et al (2000).

The most widely used models of regional economic impacts are versions of inter-industry 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.

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 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 nonfarm 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 as: 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.

Table 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	1,037.9*	319,904	25,086,809	18,543	7,208
San Bernardino	1,709,434	*	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/)

Note: *Data for Riverside-San Bernardino PMSA

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 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.

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 Earthquake Engineering International's (EQE) Early Prediction 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.

B Application: Towards determining the full costs an Elysian Park 7.1 maximum credible event

B.1 Modeling approach

Figure 1 summarizes our approach. Implementing this approach is a data intensive effort. SCPM2 aggregates the Southern of California Association of Governments (SCAG) 1,527 traffic analysis zones (Figure 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 1997) 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.

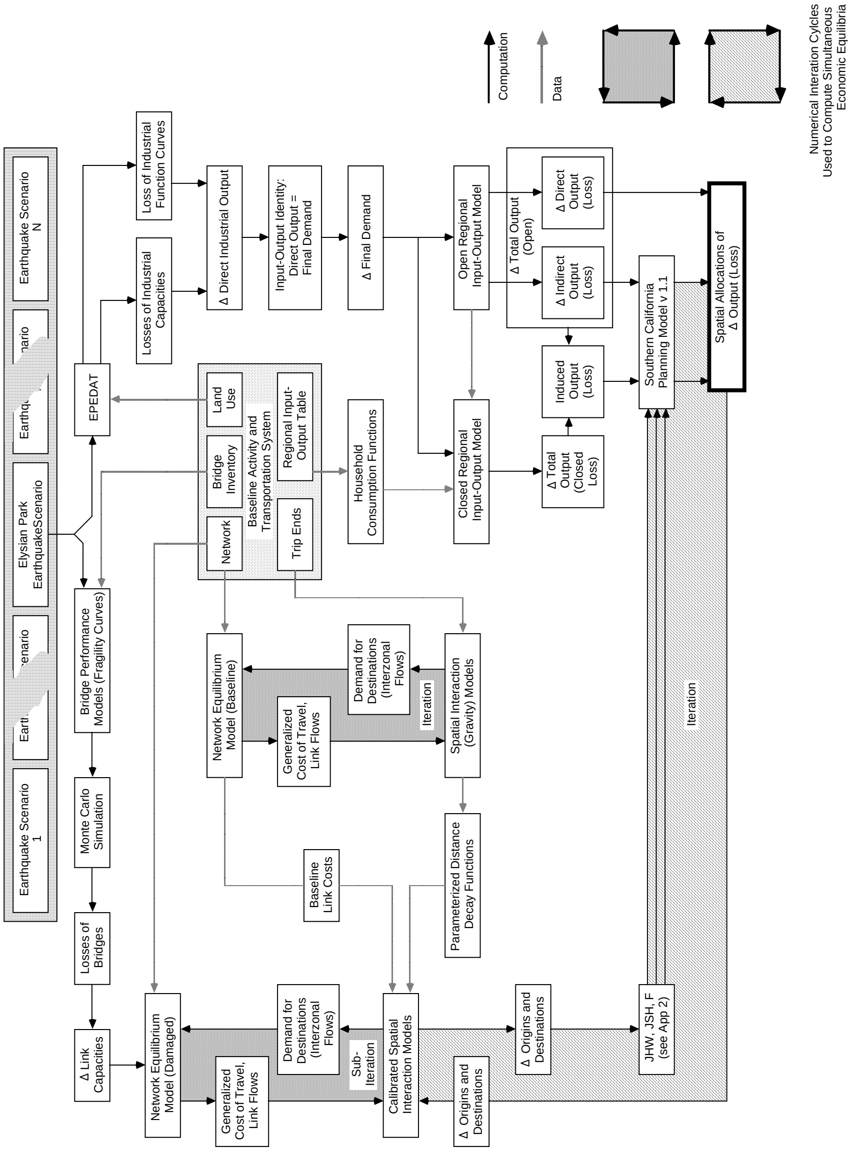

Figure 1 Summary of the Southern California Planning Model 2 (SCPM2)

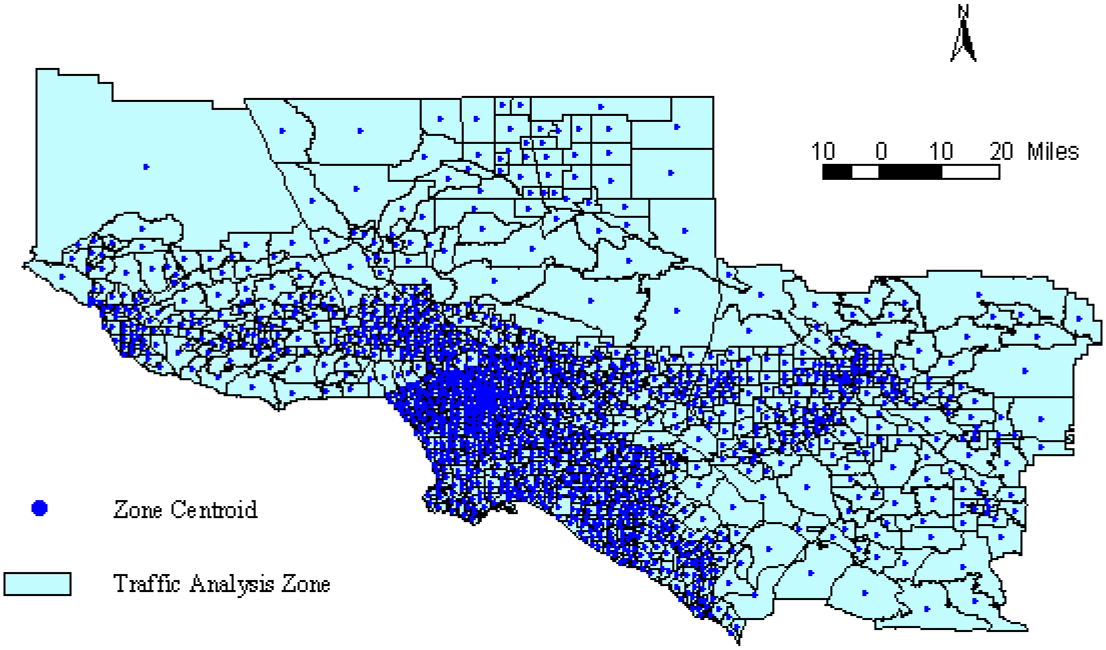

Figure 2 1,527 Southern California Association of Governments (SCAG) Traffic Analysis Zones.

B.2 Establishing a baseline

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.

SCPM1 includes work and shopping (including service) trips, but not other non-work travel and freight flows. The SCAG origin-destination data includes requirements for work and non-work trips, but not freight flows. We mapped the five-county, 1,527-zone SCAG transportation network to the 308-zone SCPM activity system. This expresses the scaled inter-zonal flows associated with the regional transportation network in terms of flows between SCPM zones.

Each element in the SCPM1 journey-from home to-work (**JHW**) matrix describes the proportion of workers residing in zone i who work in zone j relative to the total employment in zone j. Each element of the SCPM1 journey-from home to-shop (**JHS**) matrix describes the proportion of shoppers residing in zone i who shop in zone j relative to total to the total number of shoppers in zone j. The SCPM1 **JHW** matrix is based on spatial distributions extracted from 1990 census data. The SCPM1 version of the **JHS** matrix is the result of a gravity model estimation. In the SCPM2 extension developed in this research, the elements of the **JHW** and **JHS** matrices are endogenized as a simultaneous function of network costs and estimated gravity model parameters.

Some of the model's 17 economic sectors involve freight flows. We account for these in four categories,

- nondurable manufactured goods
- durable manufactured goods
- mining (including petroleum), and

- wholesale.

Freight flows include intermediate flows to production facilities, as well as flows to final demand sites inside and outside the region. This includes import and export flows, but not flows to and from residential sites. Most of these latter flows correspond to shopping and service trips. Export flows satisfy final demand outside the region. Some import flows satisfy final demand within the region, and some are inputs to production processes. Some import and export flows also appear as throughputs. Data on the area's trade flows had to be assembled from a variety of sources. This presented some difficulties because imports and exports are reported for the Customs District, an area larger than the metropolitan area. Also, some of these reported flows are simply transshipped via the Los Angeles area.

Given the SCPM input-output relationships describing input requirements per unit of output, and given baseline jobs by economic sector and zone from the Census Transportation Planning Package (CTPP) made available to SCAG by the U.S. Bureau of Transportation Statistics (1990), the next step is to compute the total commodity i required to support production in zone z,

$D^z_i = \Sigma_j a_{i,j} \bullet X^z_j$ + sector i shipments to zone z from transshipment zones (imports) and from other zones to accommodate local final demand not associated with households; (**1.**)

where X^z_j = the total output of commodity j in zone z given base year employment in sector j and zone z, and

$a_{i,j}$ = the i, jth element of **A**, the matrix of value demand coefficients for the (open) input-output model. This is the flow from i to j per unit output of j.

The first term on the right hand side of equation (**1.**) accounts for inter-industry shipments out of all zones by aggregate freight sector i. Because this summation applies to the open input-output model, D^z_i excludes most shipments to households. In the open model, households generate local final demands, but no intermediate demands. Most shipments associated with this final demand are treated as shopping trips. D^z_i is the total flow of commodity i supplied from everywhere to all non-final demand activities in zone z.

Similarly, we compute total supply of output i furnished by zone z,

$O^z_i = \Sigma_j s_{i,j} \bullet X^z_i$ + sector i shipments to transshipment zones from zone z to accommodate nonlocal final demand (exports) and to other zones to accommodate local final demand not associated with house-holds; (**2.**)

where X^z_i = the total output of commodity i in zone z given base year employment in sector i and zone z, and

$s_{i,j}$ = the i, jth element of **S**, the matrix of value supply coefficients for the (open) input-output model. This is the flow from i to j per unit output of i.

The first term on the right hand side of equation (**2.**) accounts for inter-industry shipments out of zone z by aggregate freight sector i. The product being summed in this term is the flow from sector i in zone z into any sector j anywhere in the region. Like D^z_i, O^z_i excludes most shipments to households. As in the case of (**1.**), these shipments consist of shopping trips. O^z_i is the total flow of aggregate freight commodity i supplied from zone z to all activities everywhere.

Value flows O^z_i supplied by activity j and originating in zone z and value flows D^z_i demanded from activity i and terminating n zone z must be translated into freight trip productions P^r_i and attractions A^s_i associated with activity i in zone z. Using conversion factors constructed from the 1993 Commodity Flow Survey (CFS, U.S. Department of Transportation 1997), we convert all value flows D^z_i and O^z_i \$ values to truckload equivalents. The CFS describes freight flows in terms of \$/ton for the major industrial sectors. The 1992 census of transportation (U.S. Bureau of the Census 1993b) describes tons/truck. This permits calculation of a coefficient, η_i, relating the value of shipments to zonal transportation requirements, typically passenger car units (PCU).

$$\begin{aligned} P^r_i &= \eta_i \bullet O^z_i \\ &= \text{trip production of commodity i in origin zone } z = r, \end{aligned} \qquad (\mathbf{3.})$$

and

$$\begin{aligned} A^s_i &= \eta_i \bullet D^z_i \\ &= \text{trip attraction of commodity i to destination zone } z = s \end{aligned} \qquad (\mathbf{4.})$$

Based on SCAG's network equilibrium costs for flows between zones r and s, $c_{SCAG}{}^{r,s}$, and the trip production and attraction vectors determined in steps above, we calibrated nine separate spatial interaction models. These include nine flows involving people,

- home-to-work,
- work-to-home,
- home-to-shop,
- shop-to-home,
- home-to-other,
- other-to-home, and
- other-to-other;

and four classes of commodity flows. We estimated each of these thirteen matrices of inter-zonal flows separately, but in response to a common measure of network equilibrium costs. The structure of inter-zonal flows in each of these matrices influences network equilibrium costs. Thus, this baseline calibration required iteration between the network assignment model and the set of gravity models. The objective of these baseline gravity model calibrations was to estimate distance decay parameters (Wilson 1970). These distance decay parameters are used to predict travel demand following an earthquake. Also, once estimated, the home-to-work and home-to-shop matrices were converted to the **JHW** and **JHS** matrices by striking proportions in columns, i.e., relative to the total number of trips terminating in zone j. This integrated modeling approach led to successful numerical convergence, making formulation of a simultaneous destination and route choice mode unnecessary.

We relied on a singly-constrained gravity model formulation in the case of freight because we did not have trip interchange matrices for freight sectors. The parameters of the singly-constrained formulation were calibrated based on the following criteria (Putnam 1983),

$$\underset{\beta_i}{\text{Minimize}} \, \Sigma_r \, |P^r_i(\beta_i) \bullet ln(P^r_i) - \Sigma_r \, P^r_i(\beta_i) \bullet ln(P^r_i(\beta_i))|, \qquad (\mathbf{5.})$$

where β_i = distance decay coefficient for sector i;

$P^r{}_i(\beta_i)$ = estimated trip production of commodity i in origin zone r

$= \Sigma_s A^s{}_i \bullet [B_i{}^r \bullet exp(-\beta_i \bullet c^{r,s}) / \Sigma_r B_i{}^r \bullet exp(-\beta_i \bullet c^{r,s})];$ **(6.)**

$c^{r,s}$ = generalized cost of transportation from origin zone r to destination zone s;

$P^r{}_i$ = trip production of commodity i in origin zone r;

$A^s{}_i$ = trip attraction of commodity i to destination zone s; and

$B_i{}^r$ = constant specific to sector i and origin zone r, the square root of the number of total employees in origin zone r.

We constructed production and attraction vectors for each freight sector using equations (**1.**), (**2.**), (**3.**), and (**4.**). Given initial values for transportation costs and gravity model parameters, we proceeded by estimating inter-zonal flows for sector i and calculating trip productions implied by these flows. Trip attractions are fixed. For each sector, the value of β_i was adjusted to move the estimated values $P^r{}_i(\beta_i)$ toward the target values $P^r{}_i$.

We had more information about flows involving people. We had SCAG's empirically estimated trip interchange tables for the nine classes of flows described above. The availability of these interchange matrices made it possible to estimate a doubly-constrained gravity model. Estimated flows of commodity i between zones r and s, $t^{r,s}{}_i$, are a function of the flows originating in zone r, terminating in zone s, and distance decay parameters describing how travel cost affects destination choice,

$t^{r,s}{}_i(\boldsymbol{\beta}) = P^r{}_i \bullet A^s{}_i \bullet [B_i{}^r \bullet H_i{}^s \bullet \beta_{0,i} \bullet exp(-\beta_{1,i} \bullet c^{r,s}) \bullet c^{r,s(\beta_{2,i})}].$ **(7.)**

where

$\beta_{0,i}$, $\beta_{1,i}$, and $\beta_{2,i}$ = elements in a vector of distance decay coefficients for sector i;

$c^{r,s}$ = generalized cost of transportation from origin zone r to destination zone s;

$P^r{}_i$ = trip production of flow i in origin zone r;

$A^s{}_i$ = trip attraction of flow i to destination zone s;

$B_i{}^r$ = constant specific to sector i and origin zone r

$= [\Sigma_s A^s{}_i \bullet H_i{}^s \bullet \beta_{0,i} \bullet exp(-\beta_{1,i} \bullet c^{r,s}) \bullet c^{r,s(-\beta_{2,i})}]^{-1}$; and **(8.)**

$H_i{}^s$ = constant specific to sector i and origin zone rs

$.= [\Sigma_r P^r{}_i \bullet B_i{}^r \bullet \beta_{0,i} \bullet exp(-\beta_{1,i} \bullet c^{r,s}) \bullet c^{r,s(-\beta_{2,i})}]^{-1}.$ **(9.)**

The vector $\boldsymbol{\beta}$ is was adjusted to match the observed travel distribution, which depends on the observed flows $t^{r,s}{}_i$ and the equilibrium network costs $c^{r,s}$.

In all cases, equilibrium transportation costs $c^{r,s}$ were initialized as $c_{SCAG}{}^{r,s}$, based on estimated link flows and costs provided by the Southern California Association of Governments. The parameters that minimize (**5.**) and match the travel time distributions for observed flows also imply a set of 13 trip interchange matrices. Summing the 13 trip interchange matrices provided a new set of flows, expressed in PCUs, and associated equilibrium network costs $c^{r,s}$. These costs were fed back into each of the gravity models. The matrix of equilibrium network costs **c** and the vector of distance decay parameters β were iteratively adjusted until consistent travel demands and travel costs are computed. The end result is a matrix of equilibrium link costs $c^{*r,s}$ consistent with a corresponding set of equilibrium trip interchange matrices consisting of elements $t^{*r,s}_i$.

The information needed to model the baseline with the internal consistency described here 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.

B.3 The Elysian Park maximum credible event scenario

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 3 provides a map of predicted peak ground accelerations by 1990 census tract for this event.

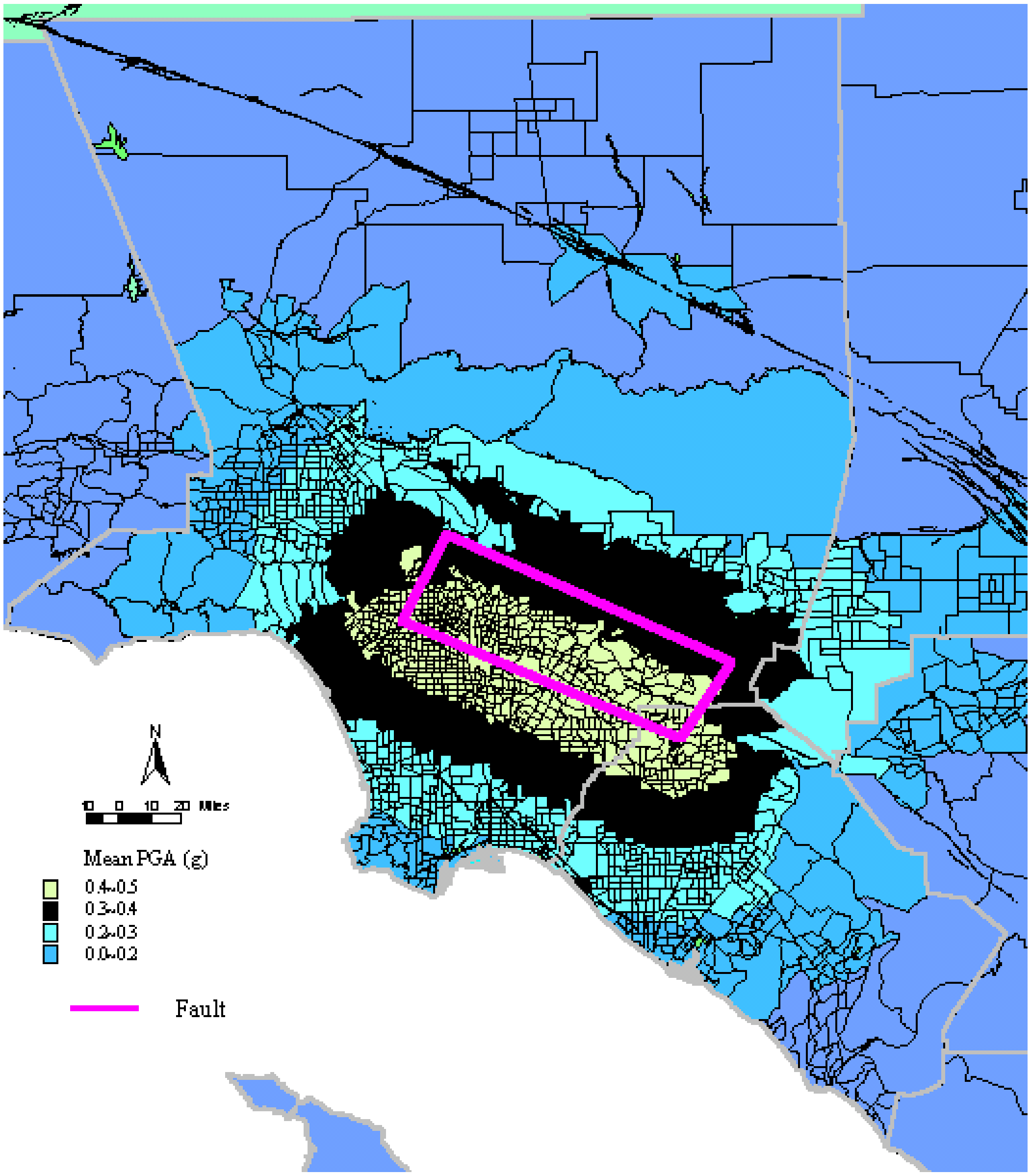

Figure 3 Predicted Peak Ground Accelerations for a Magnitude 7.1 Earthquake on the Elysian Park Blind Thrust Fault.

Bridge fragility curves

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 2.

Empirical fragility curves (Shinozuka 1998, 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.

The likelihood function is expressed as,

$$L = \prod_{i=1}^{N} \left[F(a_i)\right]^{x_i} \left[1 - F(a_i)\right]^{1-x_i} \;, \qquad \textbf{(10.)}$$

where 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

$$F(a) = \Phi\left[\frac{\ln\left(\frac{a}{c}\right)}{\zeta}\right] \qquad \textbf{(11.)}$$

where a = PGA value,

c = median,

ζ = logstandard deviation, and

M[ ] = is the standardized normal distribution function.

The two parameters c and ζ in Equation 2 are computed as c_0 and ζ_0 maximizing the log of the likelihood function, ln L, and hence L.

$$\frac{d\ln L}{dc} = \frac{d\ln L}{d\zeta} = 0\,. \qquad \textbf{(12.)}$$

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

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 are 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 is 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 4). The medians and log-standard deviations of these fragility curves are given in Table 2.

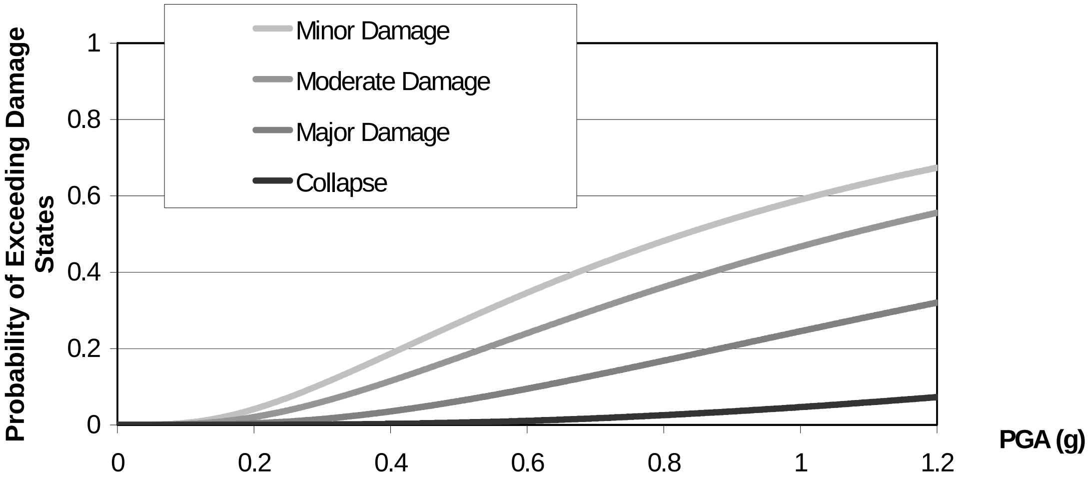

Figure 4 Bridge Fragility Curves Estimated from Caltrans Northridge Earthquake Data

Table 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

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.

Modeling losses

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, as explained above, nine classes of passenger flows were combined with four classes of freight and loaded on a common network.

Aggregate results for the Elysian Park scenario

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 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 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. This results in a substantial retention of transportation network capacity, and a relatively small increase in transportation costs of almost $1.5 billion.

III. BRIDGE RECONSTRUCTION

A. Problem statement

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.

B. Application of SCPM2 to the evaluation of bridge reconstruction strategies

B.1 Bridge repair costs

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.

Row D in Table 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 well accounted for at this point. 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 be 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.

Spatially disaggregated results for the Elysian Park scenario

SCPM2 provides unprecedented disaggregation of economic impacts over metropolitan space. 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.

Table 3 Total Loss ($Billions): Elysian Park Magnitude 7.1 Earthquake,
Maximum Simulated Disruption to Baseline Transportation (Closure at BDI ≥ 0.75)

Loss Type	Baseline		Elysian Park Scenario: Conservative 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. RSRI Model.
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.

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 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.

B.2 Network delay costs: Alternative reconstruction strategies

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.

There is considerable interest in efficient bridge reconstruction approaches. SCPM2 is well suited to comparing the economic benefits of alternative schemes. Figure 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 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 3.

The lower bound in Figure 5 describes the network user costs on an undamaged network, $25.839 billion (Table 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.

C. 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.

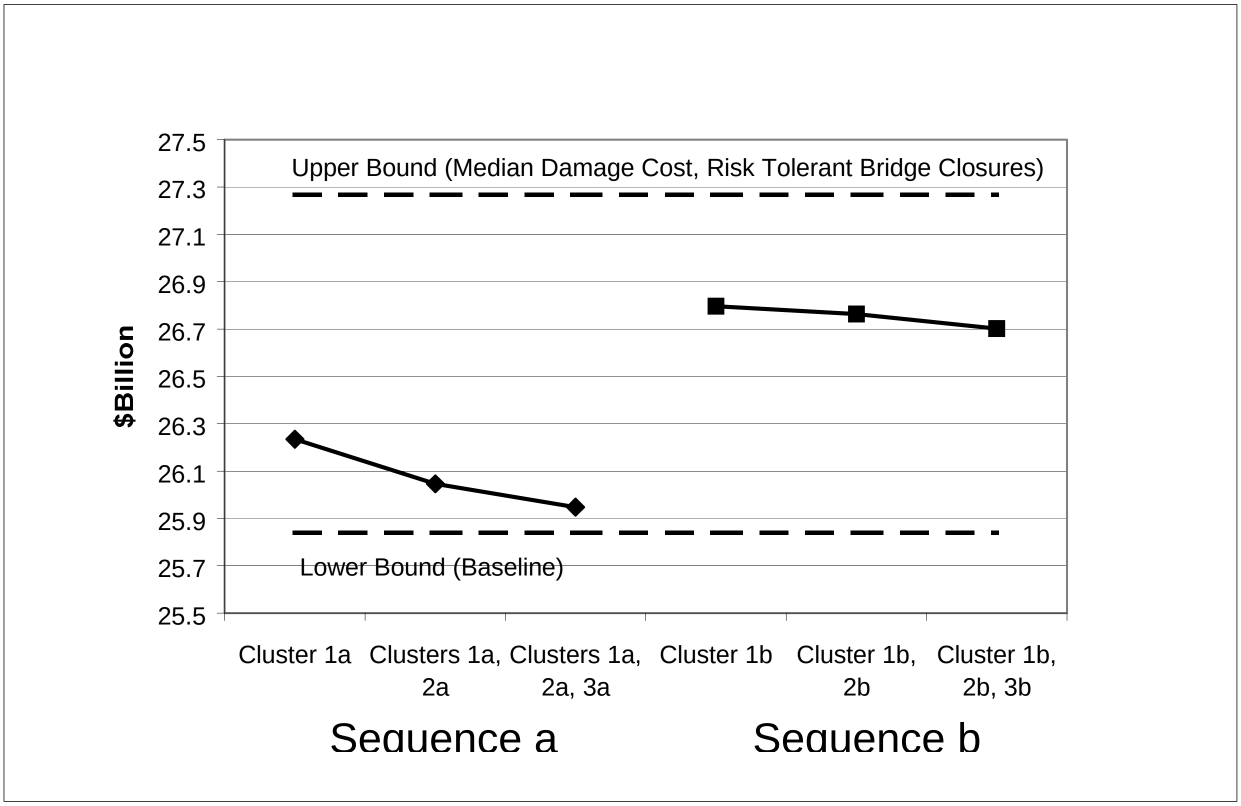

Figure 5 Transportation Network Costs of Two Alternative Cluster Repair Sequences.
Source: Cho, et al (2000).

IV. SCPM2 extensions endogenizing work and shopping trip attractions and productions

In the applications of SCPM2 illustrated in Sections II and III, all distance-decay functions were endogenously determined. 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. Doing so requires a modification of the convergence procedure discussed in Section II. The following four models implement these changes. The resulting elaboration of SCPM2 is convergent. The algorithms for implementing these changes are given in the Appendix.

1. Changing work trip attractions (ΔA_{p1}^{z})
    a. We have spatially allocated the direct impacts
    b. Change in trips attracted to each zone = *f* (total job impacts by zone)
    c. We do not know the full impacts until the model has converged

$$\Delta A_{p1}^{z} = f(V_d^{z} + V_i^{z} + V_u^{z})$$

2. Changing work trip productions (ΔP_{p1}^{z})
    a. Reductions in work trips produced in and attracted to each zone should be consistent with the baseline journey-from-home-to-work matrix, JHW
    b. $JHW * (A_{p1}^{z} - \Delta A_{p1}^{z}) = P_{p1}^{z} - \Delta P_{p1}^{z}$

3. Changing shopping trip productions (ΔP_{p3}^{z})
    a. Reduced employment and fewer work trips reduce household income, which reduces shopping trips produced in each zone.
    b. Assume a fixed $ amount per shopping trip.
    c. Assume the relationships between changes are linear, i.e., changes are proportionate.
    d. $P_{p3}^{z} := P_{p3}^{z} \cdot \left[\dfrac{P_{p1}^{z} - \Delta P_{p1}^{z}}{P_{p1}^{z}} \right]$

4. Changing shopping trip attractions (ΔA_{p3}^{z})
    a. Reduced retail sector activity reduces employment in the retail sector, which reduces the number of shopping trips attracted to each zone.
    b. $A_{p3}^{z} := A_{p3}^{z} \cdot \left[\dfrac{X_{retail}^{z} - V_{retail}^{z}}{X_{retail}^{z}} \right]$

In the results that follow, we have applied these models to the problem of endogenizing shopping trip ends. Table 4 summarizes transportation network cost results for several representative bridge damage and bridge damage scenarios. Scenarios are defined in terms of bridge closure policies and the pre-earthquake traffic volumes (maximum versus median) affected by bridge closures. Closing only severely damaged bridges (DS = 0.75) is a risk tolerant policy. Row 5 in each table modifies the results in row 1 by adding the effects of shopping trip end adjustments. The nature of earthquake-induced adjustments in work trip ends remains an important research question.

Table 4 Total Travel Cost (before repairs) by Earthquake Scenario (Passenger Car Units * Minutes)

Total Travel Cost (before repairs) by Earthquake Scenario (Passenger Car Units * Minutes)

	Driver Delay	Freight Delay	Total Delay
Baseline	85,396,813	10,298,781	95,695,594
DS=0.30 Max	225,830,486	28,285,954	254,116,440
DS=0.30 Median	117,493,842	15,602,872	133,096,713
DS=0.75 Max	94,349,424	11,581,677	105,931,101
DS=0.75 Median	89,945,131	10,966,123	100,911,255
DS=0.30 Max-Shop	90,175,132	10,483,089	100,658,221

Total Travel Cost (before repairs) by Earthquake Scenario ($Billions)

	Driver Delay	Freight Delay	Total Delay
Baseline	21.290	4.550	25.839
DS=0.30 Max	56.300	12.495	68.795
DS=0.30 Median	29.291	6.893	36.184
DS=0.75 Max	23.522	5.116	28.638
DS=0.75 Median	22.424	4.844	27.268
DS=0.30 Max-Shop	22.481	4.631	27.112

Changes in Total Travel Cost (before repairs) by Earthquake Scenarios (PCU * Minutes)

	Driver Delay	Freight Delay	Total Delay
Baseline	-	-	-
DS=0.30 Max	140,433,673	17,987,173	158,420,846
DS=0.30 Median	32,097,029	5,304,091	37,401,119
DS=0.75 Max	8,952,611	1,282,896	10,235,507
DS=0.75 Median	4,548,318	667,343	5,215,661
DS=0.30 Max-Shop	4,778,318	184,309	4,962,627

Changes in Total Travel Cost (before repairs) by Earthquake Scenarios ($ Billions)

	Driver Delay	Freight Delay	Total Delay
Baseline	-	-	-
DS=0.30 Max	35.010	7.946	42.956
DS=0.30 Median	8.002	2.343	10.345
DS=0.75 Max	2.232	0.567	2.799
DS=0.75 Median	1.134	0.295	1.429
DS=0.30 Max-Shop	1.191	0.081	1.273

Notes: DS = Bridge Damage State.

V. Application of SCPM2 to the determination of bridge reconstruction costs

A. Price effects, bottlenecks, and budget forecasts

Large-scale reconstruction efforts such as those identified in Section III 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 in the manner shown in Section V.B to determine the size and location of all reconstruction employment and income effects. We do this for bridge repair budgets determined in Section III, which we now augment by the price effects that the model computes.

B. 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.

1. Some of the critical baseline data are from the 1993 PC-IO package from the Regional Science Research Institute. It includes:

X_0 : a vector of baseline total outputs for the region
A : matrix of technical coefficients for the regional economy

2. Initial Reconstruction Budget (Bridge Repair Costs, Line D, Table 3)

Various "translators" are made available by the Regional Science Research Institute. Their translator # 37 specifies plausible proportions corresponding to the final demand sectors involved with bridge and highway construction. This allows any budget to be decomposed into a vector of final demands. Analysts can then use the I-O model to calculate the full economic impacts of any major construction project. Our extension of this standard procedure is also to calculate price effects that can be expected when such budgets become large.

Bridge Damage → PC-IO translator → dY_0 (direct demand for reconstruction)
* d represents delta (change).

C. Calculation procedure

(1) Run the I-O model (closed with respect to the household sector)

$dX_0 = (I-A)^{-1}dY_0$

dW_0 : the household sector's extra income (from the last row of the transaction table) as a result of the reconstruction program.

(2) Apply an assumed overtime rate for construction sector

$dW^c_1 = dW^c_0 * 0.38$, where dW^c is labor cost of construction sectors

$dY_1 = dY_0 + dW^c_1$ (the revised budget, including labor overtime costs)

The adoption of an overtime rate was our solution to the difficult problem of evaluating labor supply elasticity effects. 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. For example, during Hurricane Andrew in Florida in 1992, it was estimated that labor costs associated with the use of some non-local labor rose by 15 percent. But would any of the 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.

(3) Run the I-O model with the revised budget

$dX_i = (I-A)^{-1}dY_1$ (next iteration, dY_{i+1} in (5) replace dY_1)

dW_i : From the last row of transaction table

(4) Calculating the price change using dW_i

$dP_i = (I-A')^{-1}*(dW_i/X_0)$

(5) Applying the price change to the budget
$dY_{i+1}=dY_1*(1+dP_i)$

(6) Repeat (3), (4), and (5) with new budget in (5) until $dP_{i+1}-dP_i=0$.

Applying this procedure generates the results in Tables 4 and 5. Each of the two tables show model I/O results for the various modeling steps described immediately above. The first column describes how 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 5, leakages are $9.62 million. In Table 6, they are $29.67 million.

We have disaggregated the 17-sector model for the construction sector because the translator provides extra levels of detail. The second column shows the same programs of expenditure if the contracting agency absorbs the 38 percent overtime charges. The third column shows 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 5 Reconstruction Budget and Interindustrial Economic Effects of Median Cost Reconstruction Activity

Scenario1 : Median Case ($71 Million)	Reconstruction Budget			Economic Effects of Reconstruction			
Sector	Initial Budget	Budget With Overtime	New Budget Considering Price Effect	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				

Table 6 Reconstruction Budget and Interindustrial Economic Effects of Mean Cost Reconstruction Activity

Scenario 2 : Mean Case ($219 Million)	Reconstruction Budget			Economic Effects of Reconstruction			
Sector	Initial Budget	Budget With Overtime	New Budget Considering Price Effect	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	4.55
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				

* Dollar in Millions

** Prime Rate for Overtime-Labor in Construction Sector = (40+128*1.5)/168=1.38

V.D 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 7 summarizes the damage associated with this scenario, and associated facility repair costs. Table 8 details the additional transportation costs incurred in the process of reconstruction. Table 9 updates Table 3 to account for the endogenous price and networks associated with the mean reconstruction cost scenario. Table 10 summarizes the mean and median reconstruction cost outcomes relative to the baseline described in Table 3.

Table 7 Bride Damage Information ($1,000)

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

Table 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 + Reconstruction)			
(PCU * Minutes)	91,702,850	11,070,634	102,773,483
($Billion)	22.862	4.890	27.752
Change Due to Reconstruction			
(PCU * Minutes)	1,757,719	104,511	1,862,228
($Billion)	0.438	0.046	0.484
Mean Reconstruction Cost Scenario			
	Passenger Delay	Freight Delay	Total Delay
Total Travel Cost (Baseline + Reconstruction)			
(PCU * Minutes)	92,349,189	11,110,640	103,459,830
($Billion)	23.023	4.908	27.931
Change Due to Reconstruction			
(PCU * Minutes)	2,404,058	144,517	2,548,575
($Billion)	0.599	0.064	0.663

Table 9 Total Losses ($Billions) Including the Impact of Endogenous Price Effects on Reconstruction Costs and Repair-Related Travel Costs: Elysian Park Magnitude 7.1 Earthquake, Maximum Simulated Disruption to Baseline Transportation (Closure at BDI ≥ 0.75)

Loss Type	Baseline		Elysian Park Scenario: Conservative Bridge Closure Criterion	
A Structure Loss[a]			$ 45.250 billion (47.96% 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 (49.54% 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
Δ Mean Repair Flow Cost[f]			2,548,575.	0.663
C Δ Total Travel Cost			7,764,236.	2.092 (2.22% of total)
D Bridge Repair Cost (Excludes Delay Cost, Includes Endogenous Price Effects)				Mean ($Billions)
				0.261 (0.28% Total)
Loss Total = A+B+C+D				$ 94.340

Notes:
a. Midpoint of EPEDAT outputs, EQE International.
b. EPEDAT, EQE International.
c. RSRI Model.
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.
f. This is the mean bridge reconstruction cost entry from the last row of Table 8.

Table 10 Bridge Reconstruction Cost Summary ($Billions)

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

Notes:
a. Table 3.
b. Table 9.

VI. CONCLUSIONS

This report has addressed 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, including increased freight and travel costs resulting from damage to the network and the supply inelasticities associated with a major bridge reconstruction effort. The report claims that this is a “full-cost” approach, but in fact the estimates derived here ($94.34 billion) are grossly underbound. There are several reasons. First, the increase in travel costs in the post-earthquake situation is minimized by adopting a risky bridge-damage-index threshold. If the more conservative threshold (BDI ≥ 0.30) had been adopted, the travel costs increase would have surged by $40 billion (?). Second, the research does not include all costs inflicted on households, other than residential structure damage itself (e.g. accommodation costs if households have to move to temporary accommodation are ignored) and increased personal travel costs because of the damaged network (but possible reductions in consumption because of the difficulty of getting to destinations are not taken into account). 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 unknown, such as the time of day when the earthquake occurred. When all these considerations are taken into account, the “full-costs” of the earthquake could be much higher.

Appendix 1: Endogenizing Passenger Trip Generation in SCPM2

The required parameters parallel the discussion in Section II. The only modification is in the third group of parameters listed below, which must now incorporate the four relationships given above.

Direct, indirect and induced impacts by zone and by sector,

$$V_d^z, V_i, V_u,$$

Baseline freight trip attraction & production in \$, and peak ratio[1]

$$D_{fi}^z, O_{fi}^z, \rho_i$$

1. Implicit in Section II, explicit here for trip accounting purposes.

Personal OD by trip purpose, peak ratio and initial JHW, JHS

$$t_{pi}^{r,s}, \rho_i \rightarrow P_{pi}^r, A_{pi}^s, {}^0JHW, {}^0JHS$$

Distance decay functions

$$\beta_{fi}, \beta_{pi}$$

Step 0: Initialization

- iteration index

$$k = 0$$

- freight trip changes in \$

$$\Delta^k D_{fi}^z = 0, \qquad \Delta^k O_{fi}^z = 0$$

- person trip production & attraction in pcu

$$P_{pi}^r = \sum_s t_{pi}^{r,s}, \quad A_{pi}^s = \sum_r t_{pi}^{r,s}, \ \Delta^k P_{pi}^r = 0, \ \Delta^k A_{pi}^s = 0$$

- initial travel cost

$${}^k c^{r,s} = c(t_{pi}^{r,s})$$

Step 1-1: Freight OD

- freight trip generation & attraction adjustment

$${}^k D_i^z = D_i^z - \Delta^k D_i^z, \qquad {}^k O_i^z = O_i^z - \Delta^k O_i^z$$

- F-factor

$${}^k F_i = \frac{{}^k O_i^z + {}^k D_i^z}{\sum_z ({}^k O_i^z + {}^k D_i^z)}$$

- freight trip generation & attraction in pcu

$${}^k P_i^r = \eta_i \cdot {}^k O_i^r, \ {}^k A_i^s = \eta_i \cdot {}^k D_i^s$$

Step 1-2: Personal OD

$${}^k P_{pi}^r = P_{pi}^r - \Delta^k P_{pi}^r, \ {}^k A_{pi}^r = A_{pi}^r - \Delta^k A_{pi}^r$$

Step2: Demand Distribution and Traffic Assignment

- increase of iteration index

  $$k := k + 1$$

- freight and personal OD

  $${}^k t_f^{r,s} = \sum_i {}^k t_{fi}^{r,s} = \sum_i f({}^{k-1}c^{r,s}, {}^k P_{fi}^r, {}^k A_{fi}^s, \beta_{fi})$$

  $${}^k t_p^{r,s} = \sum_i {}^k t_{pi}^{r,s} = \sum_i g({}^{k-1}c^{r,s}, P_{pi}^r, A_{pi}^s, \beta_{pi})$$

- JHW, JHS

  $${}^k JHW = {}^k t_{p1}^{r,s}, \quad {}^k JHS = {}^k t_{p3}^{r,s}$$

- travel cost (peak)

  $${}^k c^{r,s} = c({}^k t_f^{r,s}, {}^k t_p^{r,s}, \rho_i, \Delta network)$$

- convergence test

$$\varepsilon_f = \frac{\sqrt{\sum_{r,s,i} ({}^k t_{fi}^{r,s} - {}^{t-1} t_{fi}^{r,s})^2}}{\sum_{r,s,i} {}^k t_{fi}^{r,s}}, \qquad \varepsilon_p = \frac{\sqrt{\sum_{r,s,i} ({}^k t_{pi}^{r,s} - {}^{t-1} t_{pi}^{r,s})^2}}{\sum_{r,s,i} {}^k t_{pi}^{r,s}}$$

  if both of $\varepsilon_f, \varepsilon_p$ are small enough, stop algorithm.
  otherwise proceed to step 3

Step 3: Allocation of Impacts

- allocation of indirect impact over zones

  $${}^k V_i^z = {}^k F_i \cdot diag[V_i]$$

- allocation of induced impact over zones

  $${}^k V_u^z = ({}^k JHS)^T \cdot ({}^k JHW) \cdot {}^k F_i \cdot diag[V_u]$$

- total impact by zone

  $${}^k V^z = V_d^z + {}^k V_i^z + {}^k V_u^z$$

Step 4: Update of Freight Movement

$$\Delta {}^k D_i^z = \sum_j a_{ij} \cdot {}^k V_j^z, \qquad \Delta {}^k O_i^z = \sum_j b_{ij} \cdot {}^k V_j^z$$

Step 5: Reduction of Personal OD

- working trip

  $$\Delta {}^k A_{p1}^s = \sigma \cdot {}^k V^s, \ \Delta {}^k P_{p1}^r = JHW * \Delta {}^k A_{p1}^s$$

- shopping trip

  $${}^k P_{p3}^z = P_{p3}^z \cdot \left[\frac{P_{p1}^z - \Delta {}^k P_{p1}^z}{P_{p1}^z} \right], \ {}^k A_{p3}^z = A_{p3}^z \cdot \left[\frac{X_{retail}^z - {}^k V_{retail}^z}{X_{retail}^z} \right]$$

Go to step 1

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