INTEGRATING TRANSPORTATION NETWORK AND REGIONAL ECONOMIC MODELS TO ESTIMATE THE COSTS OF A LARGE EARTHQUAKE

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ABSTRACT

We summarize an integrated model of losses due to earthquake impacts on transportation and industrial capacity, and how these losses affect the metropolitan economy. The procedure advances the information provided by transportation and activity system analysis techniques in ways that help capture the most important economic implications of earthquakes. Network costs and origin-destination requirements are modeled endogenously and consistently. Indirect and induced losses associated with direct impacts on transportation and industrial capacity are distributed across zones and economic sectors. Preliminary results are summarized for a magnitude 7.1 earthquake on the Elysian Park blind thrust fault in Los Angeles.

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INTRODUCTION

Three research questions motivate this work. First, we want 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 want to apply such integrated models to the problem of estimating the full costs of a large earthquake, and the benefits of proposed mitigation measures. Further, because "all politics are local," we want to describe these costs and benefits at the submetropolitan level.

The benefits provided by earthquake mitigation measures consist of the costs avoided if the measures are applied. (Gordon, Richardson, and Davis 1998). But what are the full costs of an earthquake? We cannot know unless all of the interactions between infrastructure and the economy are understood. This research is an effort to trace the effects of an earthquake on the Los Angeles economy, including its impact on the transportation services delivered by the highway network. To do this, we must develop an innovative, integrated framework and methodologies for evaluating the effects of earthquakes on the services delivered by the transportation network.

To estimate these impacts, we must integrate:

- bridge and other structure performance models,
- transportation network models,
- spatial allocation models, and
- inter-industry (input-output) models.

Highway transportation systems are complex structural systems with many components. Bridge performance models are the subject of considerable investigation.

Bridges are only one kind of transportation structure, but they are also typically the most complex. Their seismic performance is difficult to model, because it is a function of design, component performance, and local factors such as peak ground acceleration (PGA) during an earthquake. See Figure 1 (Shinozuka 1998).

Work done to support this effort includes classifying bridges by local soil type, characterizing ground motion with pseudo-absolute acceleration response spectra for different soil types, modeling bridge performance by predicting the probability of exceeding a given damage state as a function of peak ground acceleration (PGA), and calibrating these models against ground motions and structural failures recorded during the Northridge earthquake.

APPROACH

Figure 2 summarizes our approach. Implementing this approach is a data intensive effort. We have available

- baseline 1990 census data describing the spatial distribution (by traffic analysis zone) of residences and workplaces by major economic sector;
- a 515 sector Regional Science Research Institute (RSRI) input output model (Stevens, Treyz, and Lahr 1983) of the Los Angeles metropolitan (five-county) economy based on 1992 economic census data (U.S. Bureau of the Census 1993a);

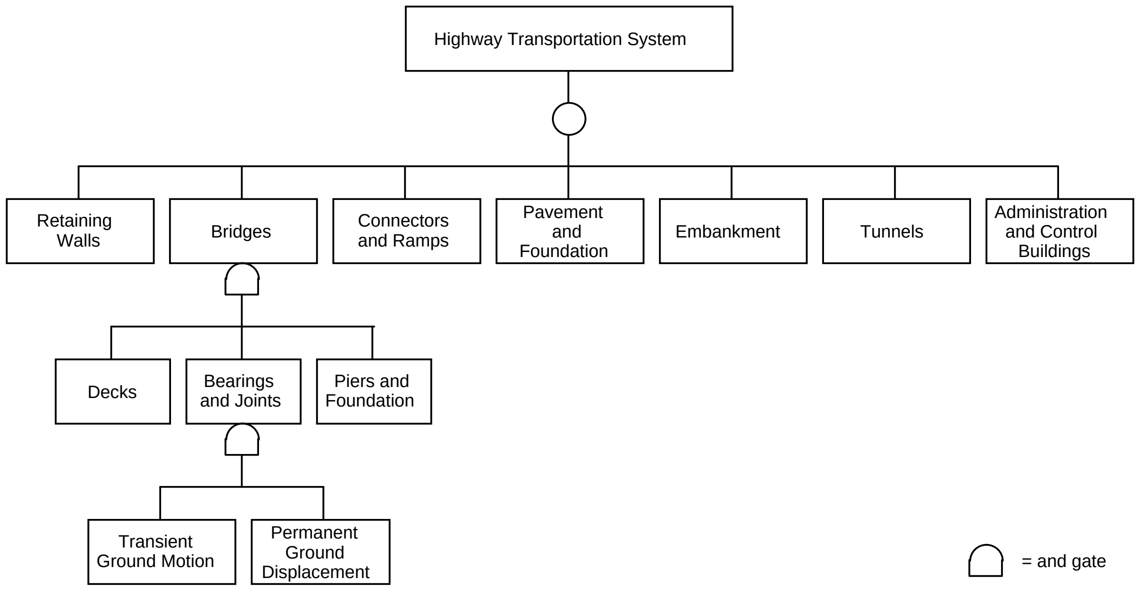

Figure 1: Design and Environmental Factors Affecting the Seismic Performance of Highway Bridges

- the 1994 transportation planning network based on data from the Southern California Association of Governments (SCAG) and California Department ofTransportation (Caltrans) Headquarters;
- 1991 SCAG Origin-Destination Survey data for 1,527 traffic analysis zones (Southern California Association of Governments 1993);
- interregional and international trade flows from a variety of sources, including studies by DRI-McGraw (1994); Booz, Allen and Hamilton; Caltrans; and the Port of Los Angeles; and
- a spatial allocation model of the same area, the Southern California Planning Model (SCPM1) (Gordon and Richardson 1994) that has been used to distribute aggregate input-output results (in $ and/or jobs) over urban space.

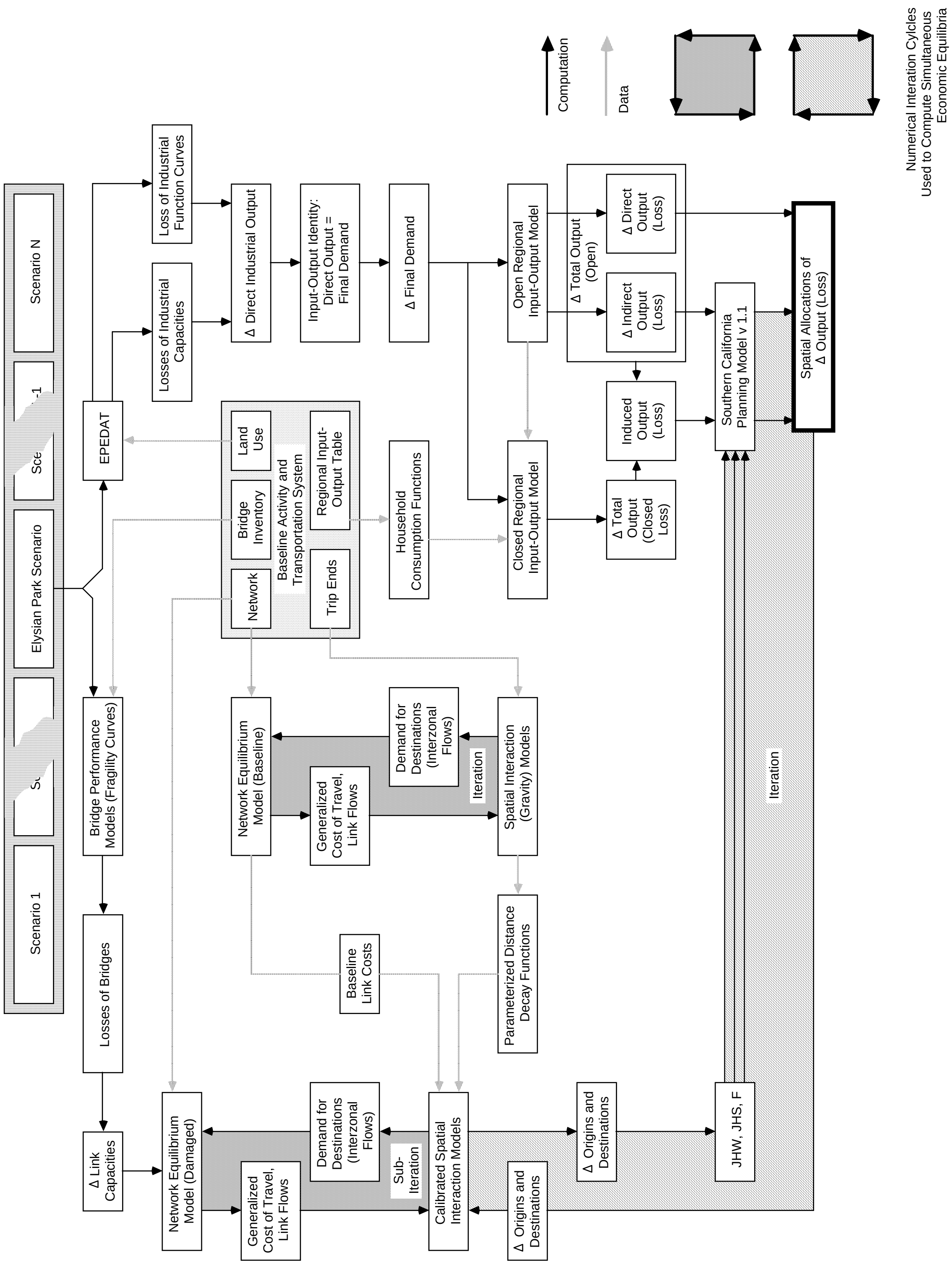

Figure 2: Summary of the Southern California Planning Model 2 (SCPM2)

The Southern California Planning Model 1 aggregates SCAG's 1,527 traffic analysis zones into 308 political jurisdictions, and aggregates the 515 sectors represented in the RSRI model to 17. Each sector uses the other sectors' outputs as inputs, and each sector supplies the other sectors with inputs. Knowledge of inter-industry transactions also makes it possible to calculate corresponding supply driven input-output coefficients (Miller and Blair 1985; Shoven and Whalley 1992). Both sets of coefficients are used for freight accounting purposes. However, input-output results are computed using the demand-driven model.

This research extends the Southern California Planning Model 1 in an important way by treating 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.

Establishing a Baseline

We want to model the effects of earthquakes on industrial capacity and system-wide transportation demand and supply. We also want to measure as fully as possible the economic impacts associated with both of these effects. Our first step is to compute a pre-event baseline that is consistent with respect to equilibrium network costs, network flows, and inter-zonal flows and origin-destination requirements.

SCPM1 treats 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 map the five county, 1,527-zone SCAG transportation network to the five-county, 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 SCPM2 extension, 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 SCPModel's 17 economic sectors involve freight flows. 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 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. Los Angeles trade flows, are summarized in Appendix 1 (available upon request).

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 requirements of output i 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

$a_{i,j}$ = is 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,

$O^z_i = \Sigma_j b_{i,j} \bullet X^z_i$ + 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 households; (**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

$b_{i,j}$ = is the i, jth element of **B**, the matrix of value supply coefficients for 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. Like D^z_i, O^z_j excludes most shipments to households. As in the case of (**1.**), these shipments consist of shopping trips. O^z_j 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 i 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_j \$ 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).

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

and

$$A^s_i = \eta_i \bullet D^z_i$$
$$= \text{trip attraction of commodity i to destination zone z = s} \quad (4.)$$

Details are available in Appendix 1.

Based on SCAG's network equilibrium costs $c_{SCAG}{}^{r,s}$ and the trip production and attraction vectors determined in steps above, we calibrate 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 estimate 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 requires iteration between the network assignment model and the set of gravity models. The objective of these baseline gravity model calibrations is the estimation of 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 are 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.

We must rely on a singly constrained gravity model formulation in the case of freight because we do not have a trip interchange matrices for freight sectors. These parameters of the singly constrained formulation are calibrated based on the following criteria (Putnam 1983),

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

where β_i = distance decay coefficient for sector i;

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

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

$c^{r,s}$ = 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 construct 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 proceed 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 is adjusted to move the estimated values $P^r{}_i(\beta_i)$ toward the target values $P^r{}_i$.

We have more information about flows involving people. We have SCAG's empirically estimated trip interchange tables for the nine classes of flows described above. The availability of these interchange matrices makes it possible to estimate distance decay parameters for a doubly constrained gravity model.

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

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

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

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

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

The vector $\boldsymbol{\beta}$ is is 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 $c^{r,s}$ are 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 provides a new set of flows, expressed in PCUs, and associated equilibrium network costs $c^{r,s}$. These costs are fed back into each of the gravity models. The matrix of equilibrium network costs **c** and the vector distance decay parameters $\boldsymbol{\beta}$ are iteratively adjusted until consistent travel demands and travel costs are computed. The result is a matrix of master equilibrium link costs $c^{*r,s}$ and a set of master equilibrium trip interchange matrices with elements $t^{*r,s}_i$.

Status Quo: Earthquake Impacts without Mitigation

The state of information needed to model the base line with the degree of internal consistency described here is sufficient to treat changes in configuration of the network and the activity system. Following an earthquake, there will 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 fragility curve analysis provide scenarios ascribing consistent losses of both types to particular events. The spatial interaction elements of our approach make 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 are treated simultaneously and consistently.

Inputs for the Los Angeles Metropolitan Area

This approach has been 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 cause major damage and casualties. 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 cause severe damage due to their proximity to metropolitan Los Angeles. The planar earthquake source representation for the Elysian Park scenario 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 displays the freeway and State Highway network for the Los Angeles metropolitan area used in this research. Los Angeles soil classes are related to Los Angeles County bridges by census tract in Appendix 2. These data make it possible to simulate changes in the Los Angeles network due to damage to bridge structures, and to combine this with estimated damage to other structures. These simulations rely on improved bridge performance models developed as part of this research (Shinozuka

Figure 3: The Los Angeles Metropolitan Area Transportation Network

1998). These bridge performance models have been calibrated against structural failures experienced during the Northridge earthquake. See Appendix 2. Table 1 relates Los Angeles bridges to estimated ranges for peak ground accelerations associated with the Elysian Park scenario. Simulated bridge failures associated with the Elysian Park scenario are displayed in Table 2 and Figure 4.

Modeling Losses

Earthquakes induce changes in industrial production due to effects on building stocks, particularly factories, warehouses, and office buildings. Damage to production facilities is translated into an exogenous change in final demand (Isard and Kuenne 1953). EQE's early post-earthquake damage assessment tool (EPEDAT) is a GIS-based

Table 1: Bridge Type and Peak Ground Acceleration by Los Angeles Census Tract

PGA (g)		Census Tract		Caltrans Bridges		City/Co. Bridges	
Range min[a]	Range max[a]	Number	Percent	Number	Percent	Number	Percent
0.00	0.05	3	0.2 %	24	1.0 %	15	1.0 %
0.05	0.10	54	3.3 %	137	5.9 %	122	7.9 %
0.10	0.15	156	9.4 %	184	7.9 %	240	15.5 %
0.15	0.20	240	14.5 %	349	15.1 %	248	16.0 %
0.20	0.25	314	19.0 %	358	15.4 %	156	10.1 %
0.25	0.30	255	15.4 %	293	12.6 %	191	12.3 %
0.30	0.35	399	24.2 %	547	23.6 %	406	26.2 %
0.35	0.40	231	14.0 %	426	18.4 %	172	11.1 %
Totals		1,652	100.0 %	2,318	100.0 %	1,550	100.0 %

Source: Shinozuka (1998). Bridge data are provided by courtesy of Caltrans.

Table 2: Simulation Results for a Hypothetical Elysian Park Earthquake Scenario: Damage Indices by Link Number

Simulation 1		Simulation 2		Simulation 3		Simulation 4	
1.0< DI ≤1.5	DI >1.5	1.0< DI ≤1.5	DI >1.5	1.0< DI ≤1.5	DI >1.5	1.0< DI ≤1.5	DI >1.5
064LA		034LA		032LA		033LA	
085LA		085LA		055LA		057LA	
112LA		090LA				058LA	
113LA		113LA				118LA	

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).

Figure 4: Simulated Bridge Failures Given Conditions Consistent with the Elysian Park Blind Thrust Fault Scenario: Darker Links Have More Failures

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. Specifically, the model relates 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 SCPM zone. Outputs are estimates of direct business interruption loss for the region by industry, month (over the first year following the earthquake), and SCPM zone. The model is adapted from research completed for the Multidisciplinary Center for Earthquake Engineering Research (Shinozuka et al. 1997). Parameter estimates are based on data from the 1994 Northridge earthquake in Los Angeles.

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. See Table 3. 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. About 72 percent of the structural damage 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.

This process is initialized by allocating indirect impacts to zones in proportion to baseline data by applying a modified version of SCPM1. See Appendix 3. SCPM1 uses the proportion of workers in each traffic analysis zone to establish the spatial distribution

Table 3: Direct Losses Resulting From Structure Damage ($Billions, Excluding Contents): Elysian Park Magnitude 7.1 Earthquake

Structure Type	Lower Bound	Upper Bound
Residential	$ 14.5 billion	$ 24.2 billion
Nonresidential		
Commercial	4.1	6.9
Industrial	2.7	4.5
Other	0.4	0.6
Nonresidential Subtotal	7.2	12.0
Structure Subtotal	$ 21.7 billion	$ 36.2 billion
Content Losses	12.2	20.4
Total	$ 33.9 billion	$ 56.6 billion

of economic activities. The modified version of SCPM1 applied here relies instead on a 17 x 1527 matrix of indices constructed from economic flows into and out of each traffic analysis zone, the elements of which are initialized as

$$F^z_i \quad =[O^z_i + D^z_i / \Sigma_z (O^z_i + D^z_i)]; \qquad \textbf{(10.)}$$

where O^z_i and D^z_i are the baseline values given by equations (**1.**) and (**2.**).

Given an initial matrix **F**, a matrix of baseline equilibrium path costs **c**, baseline interzonal shipments, baseline **JHW** and **JHS** matrices, a matrix **V(d)** of direct impacts by sector and municipality from EPEDAT, disaggregated via GIS over traffic analysis zones, and vectors of **v**(**i**) and **v**(**u**) of indirect and induced impacts by sector from the RSRI input-output model, we establish an interative sequence that spatially allocates the vectors **v**(**i**) and **v**(**u**) over the traffic analysis zones. This creates matrices **V**(**i**) and **V**(**u**). Set

$$^{k=0}D^z_i = D^z_i, \qquad \textbf{(11.)}$$

$$^{k=0}O^z{}_i = O^z{}_i, \quad (12.)$$

$$^{k=0}F^z{}_i = F^z{}_i, \quad (13.)$$

$$^{k=0}\mathbf{V}(\mathbf{i}) = {}^{k=0}\mathbf{F} \bullet \text{diag}[\mathbf{v}(\mathbf{i})], \quad (14.)$$

and

$$^{k=0}\mathbf{V}(\mathbf{u}) = {}^{k=0}\mathbf{JHS}^T \bullet {}^{k=0}\mathbf{JHW} \bullet {}^{k=0}\mathbf{F} \bullet \text{diag}[\mathbf{v}(\mathbf{u})] \quad (15.)$$

where k is an iteration counter. This initialization associates indirect and induced impacts with employment locations. The induced impacts are then distributed across residential and then commercial locations via the journey-from-home-to-work, and journey-from-home-to-shop matrices. The total impact by zone at any iteration k is

$$^{k}\mathbf{V}^z = {}^{k}\mathbf{V}(\mathbf{d})^z + {}^{k}\mathbf{V}(\mathbf{i})^z + {}^{k}\mathbf{V}(\mathbf{u})^z. \quad (16.)$$

Unlike the corresponding elements of SCPM1, the matrices **JHS**, **JHW**, and **F** are endogenous. They are updated iteratively to search for a spatial allocation of indirect and induced impacts that produces mutually consistent travel demand and network costs given simultaneous reductions in transportation demand and transportation supply. Define

$$\Delta^k D^z{}_i = \Sigma_j\, a_{i,j} \bullet {}^k V^z{}_j, \quad (17.)$$

$$\Delta^k O^z{}_i = \Sigma_j\, b_{i,j} \bullet {}^k V^z{}_i. \quad (18.)$$

These changes represent decrements in economic activity due to impact of the earthquake. They are subtracted from baseline values. Update $^kD^z{}_i$ and $^kO^z{}_i$ by defining

$$^{k+1}O^z{}_i = {}^kO^z{}_i - \Delta^k O^z{}_i \quad (19.)$$

and

$$^{k+1}D^z_i = {}^kD^z_i - \Delta^kD^z_i \quad (20.)$$

Update ^{k} **F** by defining

$$^{k+1}F^z_i = [^{k+1}O^z_i + {}^{k+1}D^z_i / \Sigma_z (^{k+1}O^z_i + {}^{k+1}D^z_i)]. \quad (21.)$$

Convert these updated values $^{k+1}D^z_i$ and $^{k+1}O^z_i$ to marginal distributions of trip productions and attractions in PCUs,

$$^{k+1}P^r_i = \eta_i \bullet {}^{k+1}O^z_i \quad (22.)$$

and

$$^{k+1}A^s_i = \eta_i \bullet {}^{k+1}D^z_i \quad (23.)$$

In SCPM1, the network is not explicit and trip making is exogenous. In SCPM2, the trip interchange matrices are adjusted sub-iteratively. The entries of the thirteen trip interchange matrices are determined by applying the baseline gravity model coefficients and network costs to the set of updated trip production and attraction elements $^{k+1}P^r_i$ and $^{k+1}A^s_i$. In the case of freight flows,

$$t^{r,s}_i = A^s_i \bullet [B_i^r \bullet exp(-\beta_i \bullet c^{r,s}) / \Sigma_r B_i^r \bullet exp(-\beta_i \bullet c^{r,s})]. \quad (24.)$$

In the case of labor, shopping, and other flows involving people,

$$t^{r,s}_i = P^r_i \bullet A^s_i \bullet [B_i^r \bullet H_i^s \bullet \beta_{0,i} \bullet exp(-\beta_{1,i} \bullet c^{r,s}) \bullet c^{r,s(\beta_{2,i})}]. \quad (25.)$$

Collectively, these inter-zonal flows combine with the earthquake damaged configuration of the transportation network to imply new endogenous network flows and costs different from the values of $c^{r,s}$. This provides an opportunity for further iteration. Given fixed trip production and attraction vectors, and fixed gravity model parameters, the feedback between network costs the trip interchange matrices attenuates. Trip distribution and network flows converge to consistent values.

The resulting trip interchange matrices imply new values for the matrices $^{k+1}\mathbf{JHW}$ and $^{k+1}\mathbf{JHS}$, which, along with $^{k+1}\mathbf{F}$, update $^{k}\mathbf{V(i)}$ to $^{k+1}\mathbf{V(i)}$ via equation (**14**.) and $^{k}\mathbf{V(u)}$ to $^{k+1}\mathbf{V(u)}$ via equation (**15.**).

The economic consequences of residential structure damage are not yet fully accounted for in this analysis. In the results reported here, labor flows are only diminished as a result of damage to employment sites. This question requires further work.

Preliminary Scenario Results for Los Angeles

Table 4 summarizes our preliminary simulation results describing the full costs of a magnitude 7.1 Elysian Park event. Row A reflects the midpoint of the range of structure damage shown in Table 3, $45.25 billion. $29 billion of this is structure loss. Row B is the sum of direct, indirect, and induced losses computed by the RSRI model of the five county, Los Angeles metropolitan area. This sum is $46.7 billion. Row C summarizes the network costs in light of reduced production and reduced network capacity, $0.2 billion. The full costs of the earthquake are therefore estimated to be $92.2 billion.

This deliberately conservative scenario is contrived to include only four bridge closures. See Figure 5. All of which are associated with facilities in locations for which there are alternative routes available. The links are assumed to remain severed for one year, and Table 4 reports annual delay costs commensurate with the costs estimated by

Table 4: Total Loss ($Billions): Elysian Park Magnitude 7.1 Earthquake

Loss Type	Baseline		Elysian Park Event (4 Network Link Failures)	
A Structure Loss[a]			$ 45.250 billion (49.1% 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 (50.7% of total)	
Network Costs[e]	PCU Minutes	$ Billions	PCU Minutes	$ Billions
Personal Travel Cost	85,396,813.	38.360	86,227,507.	38.733
Freight Cost	10,298,781.	17.542	10,215,000.	17.400
Total Travel Cost	95,695,594.	55.902	96,442,507.	56.133
Network Loss = Δ Network Costs			PCU Minutes	$ Billions
Δ Personal Travel Cost			830,694.	.373
Δ Freight Cost			(- 83,781.)	(- .143)
C Δ Total Travel Cost			746,913.	.230 (.2% of total)
Loss Total = A + B + C			$ 92.217 billion	

Notes:
a. Midpoint of interval in Table 3.
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.

EPEDAT. Total freight delay decreases. This may seem counterintuitive because damage to transportation structures reduces the supply of transportation services. But, the earthquake also reduces transportation demand. In addition, SCPM II treats

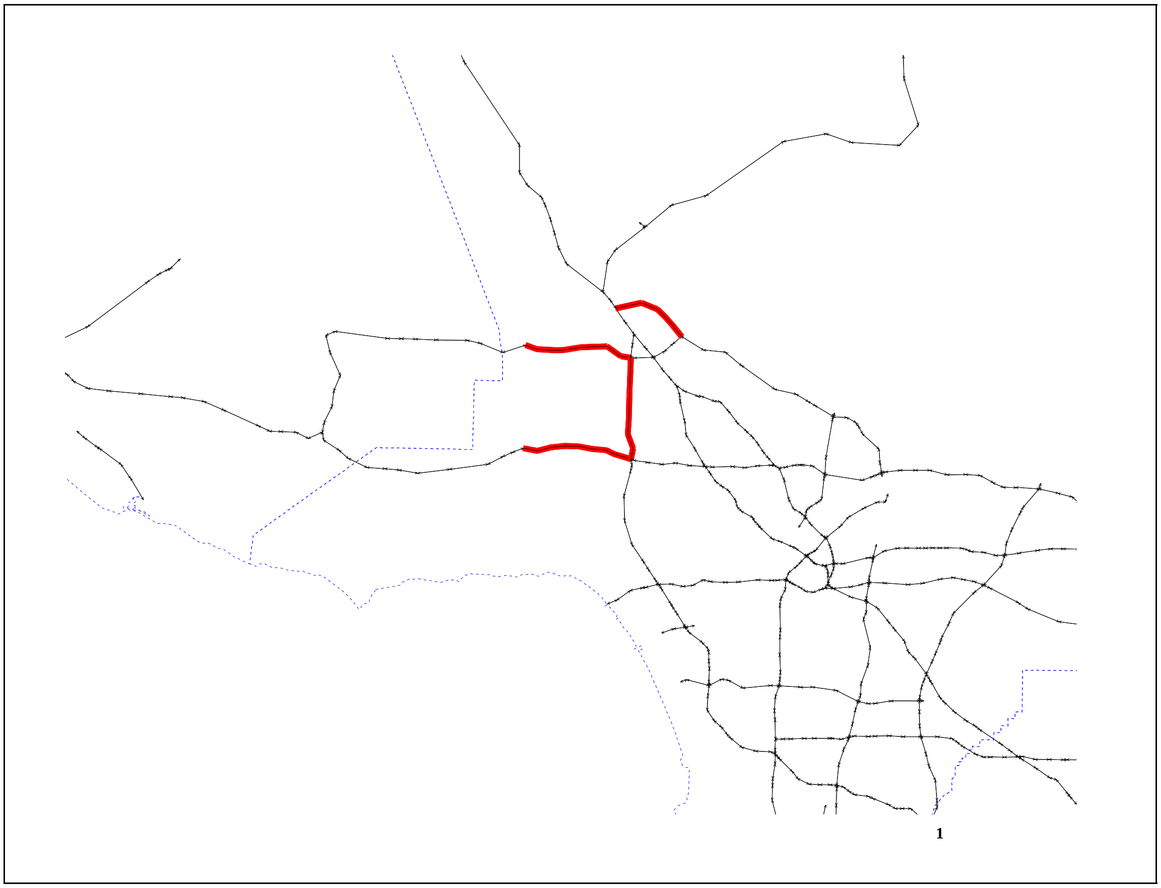

Figure 5: Four Link Failures Associated with the Elysian Park Blind Thrust Fault Scenario: Darker Links are Broken. Dashed Lines are County Boundaries.

transportation flows very endogenously with respect to network costs. Even those flows that do occur include adjustments in destinations consistent with new network costs and baseline travel behavior. Cost driven adjustments tend to result in lower costs outcomes. The net result is lower flows and lower delay.

Policy Tests: Earthquake Impacts with Alternative Mitigation Measures

We can execute this procedure for any relevant earthquake or mitigation scenario. The baseline exercise describes pre-earthquake conditions. The exercise described above summarizes post-earthquake outcomes conditioned on present levels of mitigation. These results should 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.

CONCLUSIONS

These research results permit us to assess the earthquake risk to the transportation system and the urban economy by accounting for the full range of outcomes associated with damage to bridges and production facilities. This includes the regional productivity impacts associated with the damage to the transportation system. 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 associated direct 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.

In addition to the obvious data difficulties, there are a variety of inevitable omissions at this stage of our research. The procedure does not account for the impact of transportation structure losses on final demand. The employment consequences of residential structure losses are not considered. Input-output approaches emphasize forward linkages, but ignore backward linkages. The reduced demand associated with damaged industrial facilities is included, but the consequences of constraints on industrial capacity are overlooked. We do not attempt to account for the many nonmaterial costs inflicted on the victims of earthquakes. However, we hope to add a feedback from increased freight costs to reduced household final demand.

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APPENDIX 1: Los Angeles Metropolitan Trade Flows
(Available Upon Request)

APPENDIX 2: Los Angeles Metropolitan Trade Flows

Table A2-1: Soil Class and Bridge Type by Los Angeles Census Tract

Soil Class	UBC Soil Class	Census Tract		Caltrans Bridges		City/Co. Bridges	
		Number	Percent	Number	Percent	Number	Percent
Hard rock	S1	52	3.1 %	141	6.1 %	153	9.9 %
Soft rock	S1	138	8.4 %	253	10.9 %	153	9.9 %
Soil	S2	1,462	88.5 %	1,924	83.0 %	1,244	80.3 %
Totals		1,652	100.0 %	2,318	100.0 %	1,550	100.0 %

Source: Shinozuka (1998).
Note: Soil data are from Evernden and Thomson (1988).

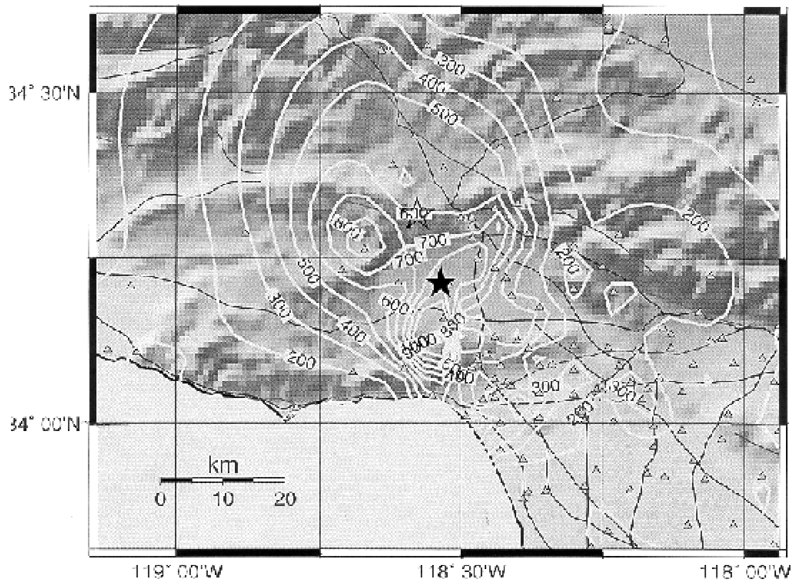
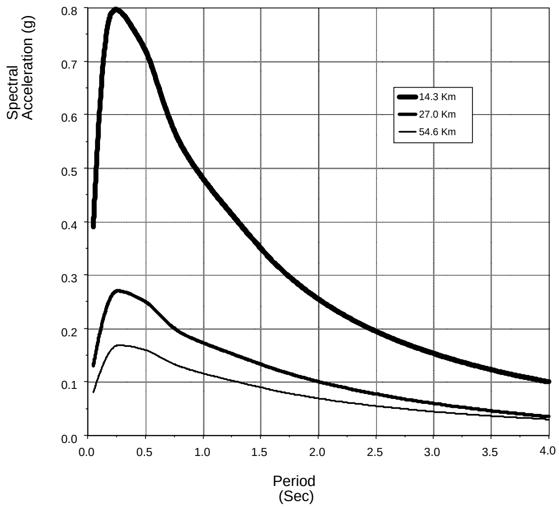
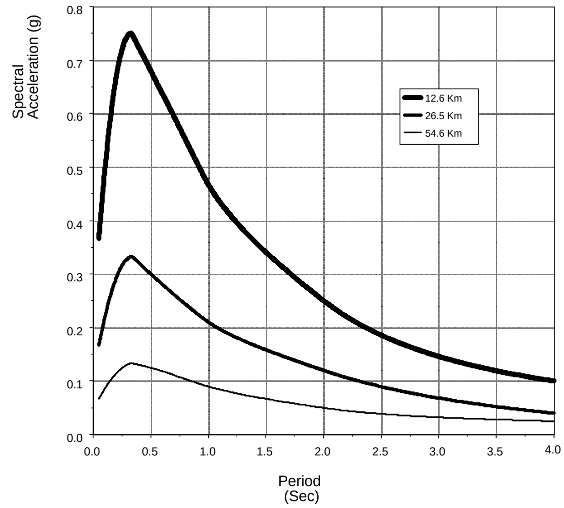


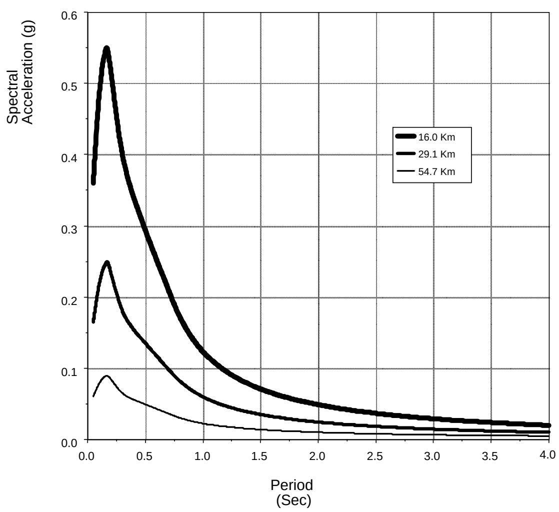
Figure A2-1: Peak Acceleration Contour Map for the Northridge Earthquake.



(a) Selected Census Tracts in Los Angeles County on Soil:



(b) Selected Census Tracts in Los Angeles County on Soft Rock:



(c) Selected Census Tracts in Los Angeles County on Hard Rock.

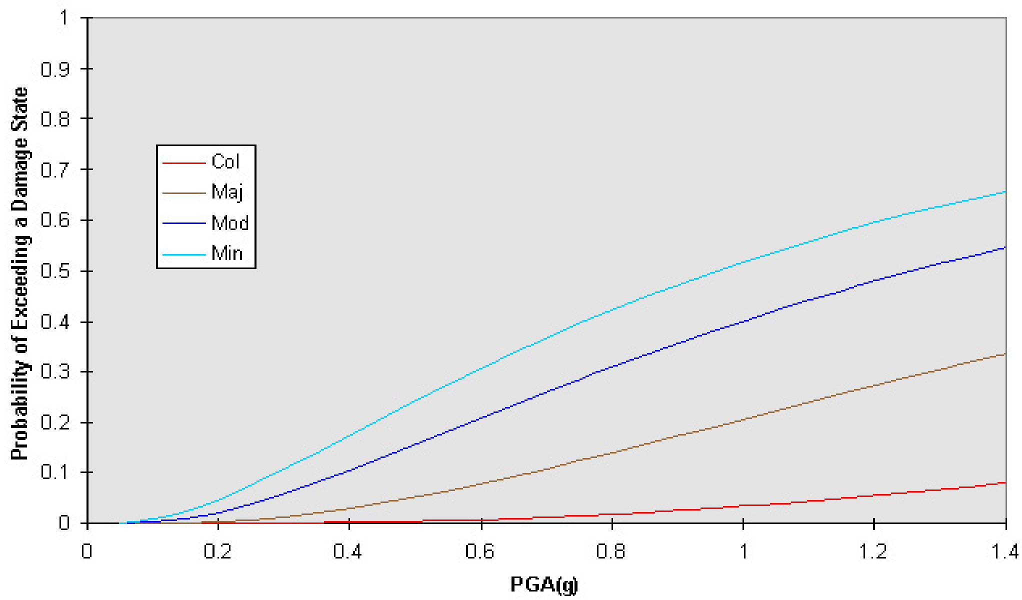
Figure A2-2: Pseudo-Absolute Acceleration Response Spectra (5% damping)

Source: Shinozuka (1998).
Note: Peak ground acceleration and spectral acceleration data are from Campbell (1997).

Table A2-2: Distribution of State and Local Bridges and the Total Number of Damaged State Bridges in the Los Angeles Metropolitan Area

County	Number of State Bridges	Number of Local Bridges	Total Number of Bridges	Total Number of Damaged Bridges
Los Angeles	2,097	1,553	3,560	228
Riverside	64	338	982	0
Orange	463	505	986	0
Ventura	324	175	504	5
Totals	2,948	2,571	5,519	233

Source: Shinozuka (1998)
Note: Bridge data are provided by courtesy of Caltrans.



Caltrans Bridges under the Northridge Earthquake (By Shinozuka)

Figure A2-3: Empirical Fagility Curves Developed for Caltrans Bridges Subjected to the Northridge Earthquake.

Table A2-3: Simulation Results for the Empircal Northridge Earthquake Scenario: Damage Indices by Link Number

Simulation 1		Simulation 2		Simulation 3		Simulation 4	
1.0< DI ≤1.5	DI >1.5	1.0< DI ≤1.5	DI >1.5	1.0< DI ≤1.5	DI >1.5	1.0< DI ≤1.5	DI >1.5
009LA	005LA	006LA	071LA	005LA	008LA	006LA	005LA
059LA	071LA	059LA	103LA	006LA	109LA	008LA	071LA
064LA	072LA	062LA	110LA	058LA	110LA	057LA	072LA
073LA	106LA	072LA		062LA		059LA	106LA
101LA	110LA	073LA		071LA		087LA	108LA
102LA	112LA	078LA		073LA		103LA	109LA
105LA		090LA		103LA		117LA	111LA
109LA		101LA		106LA		118LA	112LA
111LA		105LA		107LA			
113LA		109LA		112LA			
		111LA		117LA			
		112LA					
		113LA					

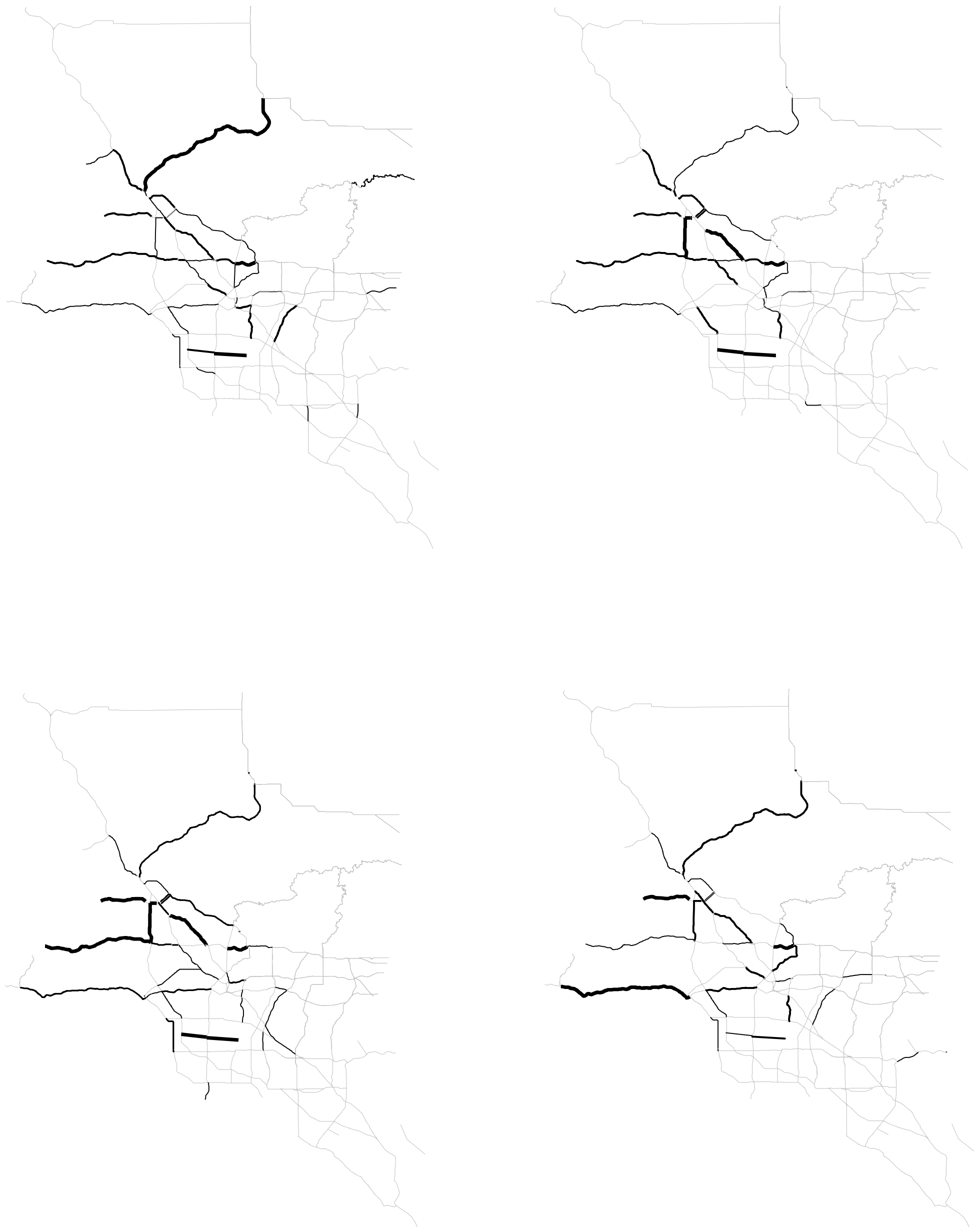


Figure A2-4: Simulated Bridge Failures Given Conditions Consistent with the Northridge Earthquake: Darker Links Have More Failures

APPENDIX 3: Southern California Planning Model 1

The Southern California Planning Model version 1 (SCPM1) is an integrated modeling approach that incorporates two basic components: input-output and spatial allocation. This approach allows the representation of estimated impacts corresponding to any vector of changes in final demand both spatially and sectorally. Changes in final demand are fed through an input-output model to generate sectoral impacts that are then introduced into the spatial allocation model.

The first model component is built upon the Regional Science Research Institute (RSRI) input – output model. This model has several advantages. These include

- a high degree of sectoral disaggregation (515 sectors);
- anticipated adjustments in production technology;
- an embedded occupation-industry matrix enabling employment impacts to be identified across ninety-three occupational groups (This is particularly useful for disaggregating consumption effects by income class and facilitates the estimation of job impacts by race.);
- an efficient mechanism for differentiating local from out-of-region input-output transactions via the use of Regional Purchase Coefficients (RPC); and
- and the identification of state and local tax impacts.

The second basic model component is used for allocating sectoral impacts across 308 geographic zones in southern California. The key is to adapt a Garin-Lowry-type model for spatially allocating the economic impacts generated by the input-output model. An initial version of this model was developed to analyze the spatial-sectoral impacts of the South Coast Air Quality Management District's Air Quality Management Plan and has been applied to other Los Angeles metropolitan-area policy problems. The building blocks of the SCPM1 are the metropolitan input-output model, a journey-to-work matrix, and a journey-to-nonwork-destinations matrix. This is a journey-to-services matrix that in the Garin-Lowry model is more restrictively described as a 'journey-to-shop' matrix).

Because Garin-Lowry models already include the concept of an economic multiplier, the key innovation associated with the SCPM1 is to incorporate the full range of multipliers obtained via input-output techniques to obtain detailed economic impacts by sector and by submetropolitan zone. The SCPM1 follows the principles of the Garin-Lowry model by allocating sectoral output (or employment) to zones via a loop that relies on the trip matrices. Induced consumption expenditures are traced back from the workplace to the residential site via a journey-to-work matrix and from the residential site to the place of purchase and/or consumption via a journey-to-services matrix.

A limitation on the conjoining of the input-output and the spatial allocation models is that the degree of sectoral disaggregation by zones is not as fine as that of the input-output sectors. In the case of the SCPM, the 494 input-output sectors are collapsed into twelve sectors to allocate impacts over 219 zones. The zones consist of nineteen identified subcenters (including the Los Angeles core area, an extended downtown), municipalities, and other intrametropolitan jurisdictions.

The generic structure of the SCPM may be summarized as follows. First, beginning with a vector of final demands, **v(d)**, total outputs from the open and closed input – output (I/O) models are calculated as

$$\mathbf{v}(\mathbf{o}) = (\mathbf{I} - \mathbf{A}_o)^{-1} \bullet \mathbf{v}(\mathbf{d}), \quad \textbf{(A3.1.)}$$

and

$$\mathbf{v}(\mathbf{c'}) = (\mathbf{I} - \mathbf{A}_c)^{-1} \bullet \mathbf{v}(\mathbf{d}); \quad \textbf{(A3.2.)}$$

where $\mathbf{A}_o$ and $\mathbf{A}_c$ are matrices of technical coefficients for the open and closed I/O models respectively; and where **v**(**o**) and **v**(**c'**) are the corresponding vectors of total outputs. The notation c' indicates that the household sector is included. We use **v**(**c**) to represent the vector of total output from the closed model for all but the household sector. By definition, **v**(**c**) may then be re-expressed as the sum of three types of output; direction (**d**), indirect (**i**), and induced (**u**).

$$\left.\begin{aligned} \mathbf{v}(c) &= \mathbf{v}(\mathbf{d}) + \mathbf{v}(\mathbf{i}) + \mathbf{v}(\mathbf{u}), \quad &\textbf{(A3.3.)} \\ \mathbf{v}(\mathbf{i}) &= \mathbf{v}(\mathbf{o}) - \mathbf{v}(\mathbf{d}), \quad &\textbf{(A3.4.)} \end{aligned}\right\} \quad (17\text{x}1)$$

and

$$\mathbf{v}(\mathbf{u}) = \mathbf{v}(\mathbf{c}) - \mathbf{v}(\mathbf{o}). \quad \textbf{(A3.5.)}$$

Equation (A.3.6) is the spatial counterpart to equation (**A3.3.**),

$$\mathbf{Z}(\mathbf{c}) = \mathbf{Z}(\mathbf{d}) + \mathbf{Z}(\mathbf{i}) + \mathbf{Z}(\mathbf{u}), \quad (17 \text{ x } 308) \quad \textbf{(A3.6.)}$$

where in each case **Z**(•) is a matrix of impacts both by spatial unit (zone) and by sector. The matrices **Z**(**d**), **Z**(**i**), and **Z**(**u**) are all specified or derived in different ways. The most straightforward of these is **Z**(**d**), which is defined exogenously, such as by an earthquake. SCPM1 allocates indirect outputs according to the proportion of employees in each sector by zone. Specifically,

$$\mathbf{Z}(i) = \mathbf{P} \bullet \text{diag}[\mathbf{v}(\mathbf{i})] \quad \textbf{(A3.7.)}$$

where **P** is a (308x17) matrix indicating the proportion of employees in each zone. The 'diag' operator diagonalizes the indicated vector into a (17x17) matrix.

The spatial allocation of induced impacts is somewhat more involved because the induced output must be traced via household expenditure patterns. Two distinct origin – destination matrixes are employed, J^{SH} (journey from services to home) and J^{HW} (journey from home to work) based on 1980 census data. Essentially, employees are traced home from work through JHW and then from home we take them back further to their shopping destinations, thereby indirectly accounting for the spatial allocation of that increment of sectoral output satisfying induced household expenditures. This may be expressed more succinctly in terms of matrix notation as

$$\mathbf{Z}(\mathbf{u}) = J^{SH} \bullet J^{HW} \bullet P \bullet \text{diag}[\mathbf{v}(\mathbf{u})]. \quad (308x308)^2\ (308x17)\ (17x17) \qquad (\textbf{A3.8.})$$

The output from SCPM1 is a (308 x 17) matrix of impacts by 17 economic sectors and 308 geographic zones.

January 17, 1994 (M6.7) Northridge Earthquake

Peak Acceleration Contour Map

Contoured Acceleration in cm/sec/sec