

ANALYZING TRANSPORTATION NETWORK RECONSTRUCTION STRATEGIES: A FULL COST APPROACH

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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 due to earthquake impacts on transportation and industrial capacity, and how these losses affect the metropolitan economy. Our approach to this problem advances the information provided by transportation and activity system analysis techniques in ways that help capture the most important economic implications of earthquakes. These full cost results have four dimensions: structure damage, business interruption, network performance, and infrastructure damage. Preliminary results for all four measures are summarized for a magnitude 7.1 earthquake on the Elysian Park blind thrust fault in Los Angeles.

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INTRODUCTION

In recent papers and reports (posted at <http://www.usc.edu/schools/sppd/>) we have demonstrated a more complete approach to accounting for the regional economic costs of earthquakes. This formulation integrated bridge performance models, transportation network models, regional input-output, and spatial allocation models. The model was presented as a means to assess the benefits of earthquake mitigation measures. Benefits consist of costs foregone. In this paper, we use the same model to begin an investigation of optimal infrastructure reconstruction strategies. In so doing, we develop a more comprehensive accounting of earthquake costs than in our previous work.

Regional scientists 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), combine a metropolitan level input-output model with a Garin-Lowry model to spatially allocate induced economic impacts, operationalizing spatial input-output analysis at the intrametropolitan level. That model does not treat the transportation network explicitly. Congestion effects are ignored, and transportation flows are exogenous.

Integrating a transportation network into SCPM-I provides important opportunities. Distance decay relationships (destination choice) can be endogenized, permitting 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 cause 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.

Four 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 cost of damage to infrastructure, and this allowed us to compare the benefits of alternative recovery strategies. Further, because "all politics are local," we wanted to describe these costs and benefits at the submetropolitan level.

To do all 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 2000) 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.

Southern California Planning Model 1 (SCPM1)

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

SCPM1 was developed for the Los Angeles metropolitan region. 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 M 7.1 event on the Elysian Park blind thrust fault. In this case, results of structure damage to businesses, as developed by EQE's EPEDAT model of structure damage, 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.

APPROACH

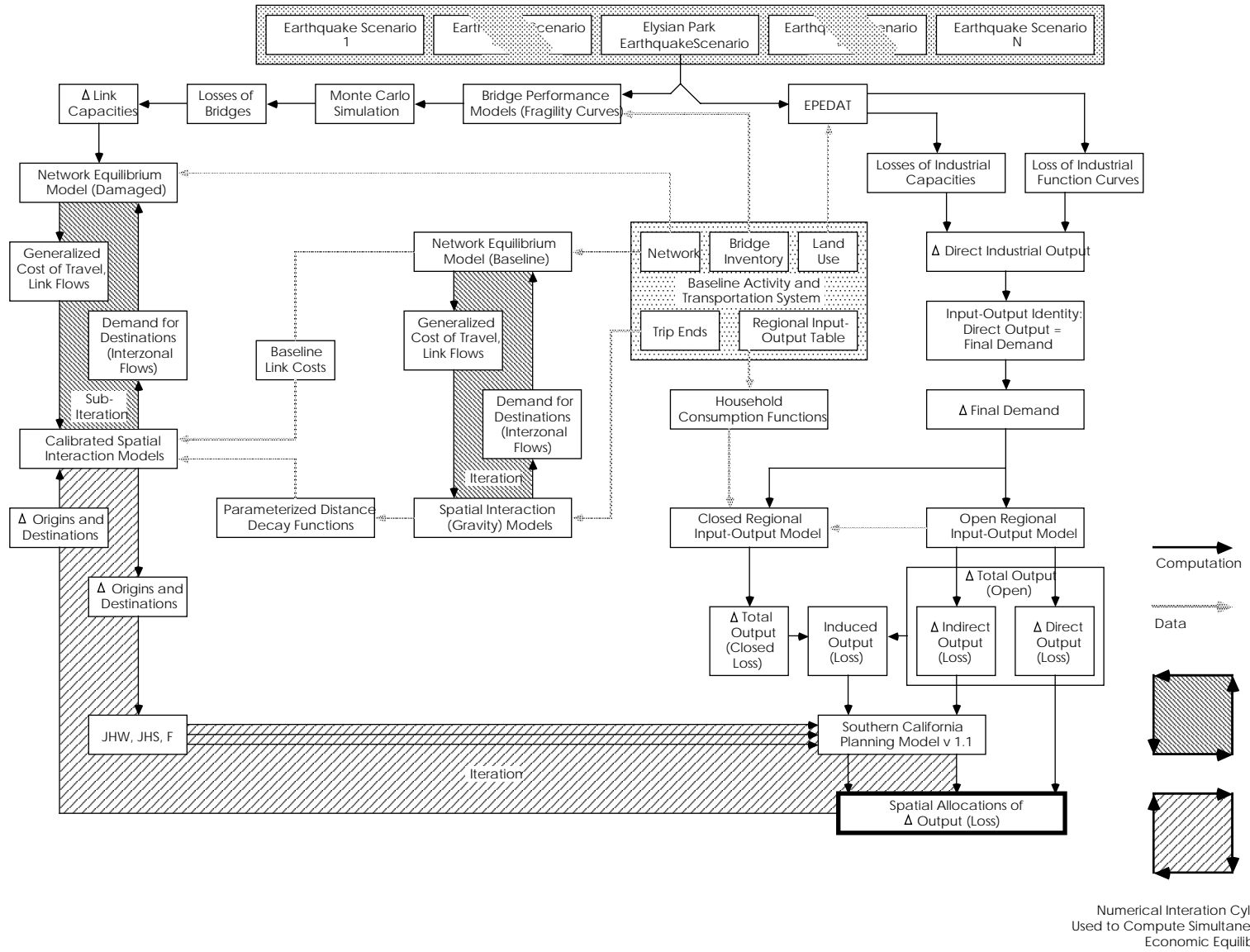
Figure 1 is a schematic representation of SCPM2. Implementing this approach involves considerable data processing and analysis. SCPM1 aggregates SCAG's 1,527 traffic analysis zones into 308 political jurisdictions, and aggregates to 17 the 515 sectors of the Regional Science Research Corporation's PC I-O model Version 7 (Stevens 1997) based

on earlier work of Stevens, Treyz, and Lahr (1983). SCPM2 extended SCPM1 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. One of our key points is that making distance decay relationships and congestion endogenous also endogenizes the spatial allocation of indirect and induced economic losses.

Establishing a Baseline

Our goal was to model the effects of earthquakes on industrial capacity and system-wide transportation demand and supply as well as to measure as fully as possible the economic impacts associated with interactions of these effects. The first step was to compute a consistent pre-earthquake baseline. We required consistent equilibrium network costs, network flows, and inter-zonal flows and origin-destination requirements.

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



SCPM1 includes work and shopping (including service) trips; missing were other non-work travel and freight flows. The regional planning agency's origin-destination data includes work and non-work trips but not freight flows. We mapped the five-county, 1,527-zone five-county transportation network to SCPM1's, 308 zone system. This expresses the scaled inter-zonal flows associated with the regional transportation network in terms of flows between local area zones.

Each element of 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 ; similarly, elements of the SCPM1 journey-from home to-shop (**JHS**) matrix describe 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 of people and employment available from the 1990 census. Whereas the SCPM1 version of the **JHS** matrix was calculated via a gravity model estimation, in the SCPM2 extension, the elements of the **JHW** and **JHS** matrices are endogenized as a simultaneous function of network costs and estimated gravity model parameters.

Only some of the model's 17 economic sectors involve significant freight flows. These are,

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

Freight flows include intermediate flows to local production facilities, as well as shipments to final demand sites inside and outside the region, including import and export flows, but not shipments to and from residential sites which correspond to shopping trips. Export flows respond to final demand outside the region. Some import flows satisfy final demand within the region, while others are inputs to local production processes. Still other import and export flows are throughputs. Data on the area's trade

flows had to be assembled from a variety of sources, presenting numerous difficult data processing challenges.

Given the available input-output relationships describing input requirements per unit of output, and given information on baseline jobs by economic sector and zone from the Census Transportation Planning Package (CTPP), the next logical step is to compute the total requirements of output i in zone z ,

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

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, j th element of \mathbf{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. 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 .

We also compute total supply of output i furnished by zone z ,

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

where X^{z_j} = 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, j th element of \mathbf{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 which, as in the case of (1.), 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 in zone z are translated into freight trip productions P^r_i and attractions A^s_i associated with activity i in zone z . Using conversion factors developed 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 to truckload equivalents. The CFS describes freight flows in terms of \$/ton for the major industrial sectors and the 1992 Census of Transportation (U.S. Bureau of the Census 1993b) cites tons/truck. From these we get, η_i , relating the value of shipments to zonal transportation requirements, typically passenger car units (PCU).

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

and

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

Based on available network equilibrium costs $c_{SCAG}^{r,s}$ and the trip production and attraction vectors developed above, we calibrated nine separate spatial interaction models, including the following nine passenger flows,

- 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 inter-zonal flows in each of these matrices influence network equilibrium costs. The baseline calibration, therefore, required iteration between the network assignment model and the various gravity models. The baseline gravity model calibrations were necessary to determine distance decay parameters (Wilson 1970) which are used to predict travel demand following a shock to the system, in this case an earthquake. Also, once estimated, the home-to-work and home-to-shop matrices were converted to the **JHW** and **JHS** matrices by inserting proportions in columns, i.e., relative to the total number of trips terminating in zone j .

We used 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 using a well known approach (Putnam 1983),

$$\text{Minimize } \sum_r |P_i^r(\beta_i) \cdot \ln(P_i^r) - \sum_r P_i^r(\beta_i) \cdot \ln(P_i^r(\beta_i))|, \quad (5.)$$

β_i

where β_i = distance decay coefficient for sector i ;

$$\begin{aligned} P_i^r(\beta_i) &= \text{estimated trip production of commodity } i \text{ in origin zone } r \\ &= \sum_s A_i^s \cdot [B_i^r \cdot \exp(-\beta_i \cdot c^{r,s}) / \sum_r B_i^r \cdot \exp(-\beta_i \cdot c^{r,s})]; \end{aligned} \quad (6.)$$

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

P_i^r = trip production of commodity i in origin zone r ;

A_i^s = 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 from equations (1.), (2.), (3.), and (4.). Given initial values for transportation costs and gravity model parameters, we estimated inter-zonal flows for sector I, 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 $P_i^r(\beta_i)$ toward the target values P_i^r .

We had more information about nine flows involving people from SCAG's empirically estimated trip interchange tables. The availability of these interchange matrices made it possible to estimate distance decay parameters for a doubly-constrained gravity model.

$$t^{r,s_i}(\beta) = P_i^r \cdot A_i^s \cdot [B_i^r \cdot H_i^s \cdot \beta_{0,i} \cdot \exp(-\beta_{1,i} \cdot c^{r,s}) \cdot c^{r,s}(\beta_{2,i})]. \quad (7.)$$

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_i^r = trip production of flow i in origin zone r;

A_i^s = trip attraction of flow i to destination zone s;

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

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

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

$$= [\sum_r P_i^r \cdot B_i^r \cdot \beta_{0,i} \cdot \exp(-\beta_{1,i} \cdot c^{r,s}) \cdot c^{r,s}(\beta_{2,i})]^{-1}. \quad (9.)$$

The vector β 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 local regional planning agency.

Parameter values that minimize (5.) and match the travel time distributions for observed flows also imply a collection of 13 trip interchange matrices. Aggregating the 13 trip interchange matrices provided a new set of flows, expressed in PCUs, along with associated equilibrium network costs $c^{r,s}$ 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 found. The final 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_j} .

Status Quo: Earthquake Impacts without Mitigation

Having accumulated the data that models the baseline with substantial internal consistency, it is possible to treat changes in configuration of the network and the activity system. Immediately after an earthquake, there will be losses of network capacity and concurrent losses of industrial capacity. The one reduces transportation capacity and raises costs. The other cuts demands on the network. Available bridge performance models and building fragility curve analysis (EPEDAT) develop consistent losses of both types to particular earthquake scenarios. The spatial interaction elements of SCPM2 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 production facilities were treated simultaneously and consistently.

An Application: The Elysian Park Scenario

SCPM2 was applied to the Los Angeles metropolitan region for the scenario presumed to be a maximum credible earthquake (magnitude 7.1) on the Elysian Park thrust ramp. While the maximum size earthquakes that seismologists believe are possible on the blind thrust faults are lower than those on the nearby San Andreas Fault, they are expected to cause severe damage due to 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, below a broad, densely populated area of central Los Angeles County, including central Los Angeles.

Bridge Fragility Curves

Bridge fragility analysis (Shinozuka 1999) determines the probability distribution of bridge damage states conditioned by bridge type and earthquake event. Detailed

results were available for the Elysian Park scenario. Damage states were defined in terms of a bridge damage index (BDI) ranging from 0 (no damage) to 1 (collapse). Yet, there still remained the key operational question is "At what bridge damage index value should the bridge be closed?" Our model allows us to systematically investigate the full cost implications of alternative bridge closure criteria.

Approximate midpoints of 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 will presumably accept as bridge closure criteria. For example, a conservative, safety oriented policy would close damaged structures to traffic, including bridges with a damage index ≥ 0.30 ; 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 . Presumably, no authority would open the most dangerous structures.

Modeling Losses

Catastrophic events cause reductions in industrial production due to effects on building stocks, including factories, warehouses, and office buildings. Damage to production facilities was treated as an exogenous change in final demand. The EPEDAT model's loss-of-function curves convert building damage to loss of production by zone and sector. Loss-of-function curves translate structural damage to business closure times and direct business interruption (production) losses. These become SCPM2 model **inputs, expressed as the percent of structures in each of four damage states by use class and by each of the 308 SCPM zones.**

In this case, 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. When 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. Almost three-quarters

of the region's structural damage to buildings is estimated to occur in Los Angeles County.

The corresponding change in final demand drives SCPM2, providing changes in output and employment for 17 sectors across 308 zones. The model provides an iterative calculation. Direct changes are exogenous and spatially identified. SCPM2 allocates indirect and induced changes spatially throughout the region in a way that respects both observed travel behavior and new network costs. The contribution of this research is the ability to more completely endogenize submetropolitan freight and passengers flows and destinations; e.g., the nine classes of passenger flows are 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 scenario earthquake. The bridge damage index score for any specific structure varies across each simulation, but each outcome is drawn from the fixed stochastic process corresponding to the Elysian Park scenario. These simulations correspond to a distribution of damaged transportation networks. Each network is characterized (in part) by a vector of dimension 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, producing two new distributions. The transportation networks in these distributions are characterized by a vector of 2,810 bridges with each bridge is now described as open (1), or closed (0).

Our model of Los Angeles is convergent. Yet, it is computationally infeasible to exhaustively investigate each network state represented in these distributions. Therefore, we selected representative members of each. The 200 simulations were rank-ordered in terms of the baseline vehicle-miles that would normally travel across the damaged links. This rank ordering made it possible to identify the simulations that are

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

An example of some simulation results describing the full costs of a magnitude 7.1 Elysian Park event are summarized in Table 1. 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 1 corresponds to median simulated disruption of baseline transportation combined with a risk tolerant bridge closure criteria that leaves moderately damaged structures open normal traffic. This results in a substantial retention of transportation network capacity, and a relatively small

Table 1: 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	[Hatched Area]		\$ 45.250 billion (48.35% of total)		
Business Loss			[Hatched Area]		
Direct Loss ^b					28.155
Indirect Loss ^c					9.627
Induced Loss ^d	8.955				
B Business Loss Subtotal	[Hatched Area]		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	[Hatched Area]		4,548,318.	1.134	
Δ Freight Cost	[Hatched Area]		667,343.	0.295	
C Δ Total Travel Cost	[Hatched Area]		5,215,661.	1.429 1.5% of total)	
D Bridge Repair Cost (Excludes Delay Cost)			Median (\$Billions)	Mean (\$Billions)	
[Hatched Area]			0.071	0.219	
Loss Total = A + B + C + D			\$ 93.487	\$ 93.635	

- 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.

increase in transportation costs of almost \$1.5 billion. Row D includes preliminary bridge repair cost estimates based on a discriminate analysis of Loma Prieta and Northridge Earthquake bridge damage states and estimated repair costs. Mean and median costs are reported. The full costs of the earthquake are estimated to be almost \$93.5 billion, close to 14 percent of GRP, although direct (business interruption) costs account for about six 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 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. 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 transportation officials provided various divergent expert estimates of the time required for repair following widespread damage.

Spatially Disaggregated Results for the Elysian Park Scenario

SCPM2 provides unprecedented disaggregation of economic impacts over metropolitan space. Tabular results, maps, and narrative summaries for this element of the research are available on our website (<http://www.usc.edu/schools/sppd>).

Corresponding results were calculated for various representative bridge-closure simulations. All of these results included the change in network costs associated with reductions in the 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 type of local impact. These costs are more difficult to disaggregate. There is insufficient information to reliably allocate these transportation costs to economic sectors, but they can be geographically distributed to traffic origins and destinations.

The 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. This can be attributed to the fact that the Southern California region has a highly redundant road and highway system. Our findings corroborate the economic importance of the regional transportation network's high levels of redundancy.

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 significant 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 version of SCPM2 is still 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 does 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.

Policy Tests: Earthquake Impacts with Alternative Reconstruction Measures

We can execute this procedure for any relevant earthquake, mitigation, or reconstruction scenario. The baseline exercise describes pre-earthquake conditions. The simulations described so far summarize post-earthquake outcomes conditioned on present levels of mitigation. These results can be contrasted with results that include various plausible 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 generated for 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 also considerable interest in efficient bridge reconstruction approaches. SCPM2 is well suited to comparing the economic benefits of alternative schemes. Figure 2 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 seven 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 2. 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 1.

The lower bound in Figure 2 describes the network user costs on an undamaged network, \$25.839 billion (Table 1). 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.

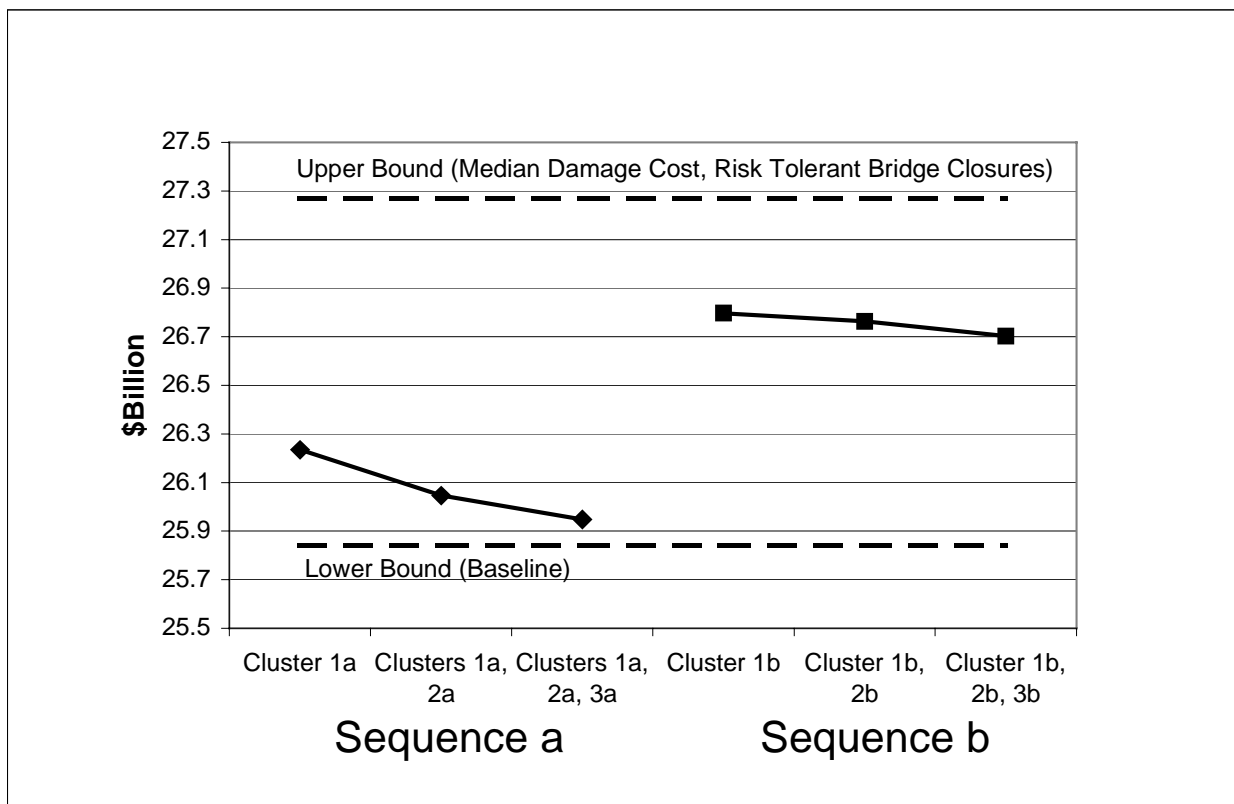


Figure 2: Transportation Network Costs of Two Alternative Cluster Repair Sequences.

CONCLUSIONS

Our integration of seismic, transportation network, spatial allocation, and input-output models permits an analysis 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.

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