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

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ABSTRACT. In this paper we summarize an integrated, operational 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

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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.

1. INTRODUCTION

Some of the most dramatic changes in regional economic and infrastructure capacity follow natural disasters. These events result in substantial economic losses associated with the disruption of the urban economy. Despite this, the existing literature on the cost of earthquakes is largely restricted to the measurement of structure and contents losses.

Three research questions motivate this work: first, 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, to apply such integrated, operational models to the problem of estimating the full costs of a large earthquake, and the benefits of proposed mitigation measures; and finally, because mitigation measures for public infrastructure are the result of a political process, and "all politics are local," we describe these costs and benefits at the submetropolitan level. To meet these objectives we have specified and operationalized a computable model of the Los Angeles economy that includes both spatial and sectoral detail.

Regional scientists have invested much time examining interindustry models. The detailed intersectoral linkages in these models are useful for exploring regional economic structure. However, this approach does not permit adequate treatment of transportation costs, not all of which are transacted because most roads are publicly provided. Recently this problem was addressed at the national level by the Bureau of Transportation Statistics effort to create Transportation Satellite Accounts (U.S. Department of Transportation, 1998, 1999).

Regional scientists are particularly interested in the spatial dimension of regional economic performance. Spatial elaborations of input-output and related approaches require explicit treatment of the resources consumed by flows between origin-destination pairs (Moses, 1955; Okuyama, Hewings, and Sonis, 1997). In these multiregional-level approaches, explicit representation of the transportation network is usually not necessary. Line-haul costs dominate congestion costs. It is another matter at the intrametropolitan level.

Intrametropolitan input-output analysis has rarely been operationalized in spatial detail. Richardson et al. (1993) provide one approach, combining a metropolitan-level input-output model with a Garin-Lowry model to spatially allocate induced economic impacts. Their model has a number of limitations including the absence of an explicit transportation network and associated congestion effects.

Adding a transportation network to this type of model provides important opportunities. For example, distance decay relationships (destination choice) can be endogenized, permitting spatial allocation of indirect economic impacts as
well as induced impacts. Further, the integration of input-output and transportation network models makes it possible to better understand the economic consequences of changes in network capacity. More recently, social science based research on earthquakes has addressed the measurement of business interruption costs (Boarnet, 1998; Gordon, Richardson, and Davis, 1998; Kawashima and Kanoh, 1990; Rose and Benavides, 1998; Rose et al., 1997). Yet, there are still few studies of the role of infrastructure and its interactions with the metropolitan economy.

In this paper we report a model that traces 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 develop an integrated framework and methodologies for evaluating the effects of earthquakes on the services delivered by the transportation network. Specifically, we integrate bridge and other structure performance models, transportation network models, spatial allocation models, and interindustry (input-output) models.

Previous Research

Reporting less than two months after the Northridge earthquake, Kimbell and Bolton (1994) relied upon a “historical analogies approach.” The nature of that approach is not clear in the report except that they used data on the effects of prior earthquakes and disasters, including the Loma Prieta quake, the Whittier quake, the Oakland fires, and the Los Angeles riots. They found 29,300 immediate job losses for Los Angeles County, with an additional 6,400 jobs lost outside the County. The authors report net positive impacts because of reconstruction later in 1994, but nevertheless, there is a long term negative impact of 18,500 jobs lost.

Using a survey approach, Boarnet (1998) sought information on the impacts of freeway damage from the Northridge earthquake. He found that 43 percent of all firms reporting any losses mentioned that some of these were because of transportation problems. Eguchi et al. (1998) reported on their application of EQE International’s Early Post-Earthquake Damage Assessment Tool (EPEDAT), a GIS-based model, to the problem of estimating Northridge losses. They calculated that these losses were in excess of 44 billion dollars.

Chang (1995) introduced multivariate techniques for post-event assessments of lifeline related losses versus those resulting from nonlifeline factors. She applied these methods to an assessment of the economic effects of lifeline disruptions in the Hanshin earthquake. Railroad capacity losses were found to be more consequential than highway losses. Rose and Benavides (1998) also applied interindustry models as a means of measuring regional economic impact analysis, emphasizing indirect costs. The authors traced and recorded the intersectoral ripple effects associated with the full impacts of electricity disruptions expected from a hypothetical 7.5 magnitude earthquake in the Memphis area. A seven percent loss of Gross Regional Product was forecast over the first 15 weeks after the event. Rose and Lim (1997) applied the same model to an

analysis of the Northridge earthquake's effects. Rose et al. (1997) developed a methodology for integrated assessment of the regional economic impacts of earthquake-induced electricity lifeline disruptions.

Cochrane (1997) elaborated on the nature of indirect economic damages, including problems with backward and forward linkages. He demonstrated that the receipt of disaster assistance matters in a full accounting of regional impacts—even though these are simply transfers within the larger national context. In addition, any resulting indebtedness merely shifts the burden to future generations. Cochrane also introduces the NIBS (National Institute of Building Standards) model to account for net regional losses and gains after all transfer payments and possible debt payments are included. Among other things, he found that indirect (nonstructure) losses are inversely proportional to the size of the sector shocked.

Okuyama, Hewings, and Sonis (1997) developed a closed interregional input-output model that emphasizes distributional effects. The approach is also sequential and applicable to earthquake-type events where there may be drastic quarter-to-quarter changes in demand and capacity. The model is applied to the Kobe earthquake. Four types of model coefficients are manipulated to simulate the disaster.

Kim et al. (1998) suggested how the Leontief and Strout (1963) multi-regional input-output model can be combined with Wilson's (1970) entropy function. Kim et al. suggested an approach that focuses on the incentives to return an interregional (substate) transportation system to pre-earthquake conditions. They discussed a procedure for matching post-earthquake flows to pre-earthquake flows as a mechanism for imputing changes in final demands.

Gordon, Richardson, and Davis (1998) applied an input-output model (Southern California Planning Model version 1, SCPM1) of the Southern California region to the problem of estimating business interruption costs of the 1994 Northridge earthquake. Their analysis found that business interruption accounted for 25–30 percent of the full costs of the earthquake. Conventional loss estimation studies focused on structure losses (what earthquake engineers refer to as "direct losses"), thereby omitting many significant costs.

As this summary indicates, there has been limited attention given to the socioeconomic impacts of earthquakes. Most of the research on earthquakes is in engineering and geology. Progress in economic impact research is more recent. Earthquake engineering is a challenging field, but exploring and integrating the economic impacts of earthquakes with engineering models is especially challenging.

Impact Models and the Southern California Planning Model Version 1 (SCPM1)

As demonstrated above, the most widely used models of regional economic impacts are versions of interindustry models. These attempt to trace intra-regional and interregional shipments, usually at a high level of industrial
disaggregation. Being demand driven, they only account for losses via backward linkages.

The Southern California Planning Model version 1 (SCPM1) was developed for the five-county Los Angeles metropolitan region, and has the unique capability to allocate all impacts, in terms of jobs or the dollar value of output, to 308 subregional zones, mostly municipalities. This is the result of an integrated modeling approach that incorporates two fundamental components: input-output and spatial allocation. The approach allows the representation of estimated spatial and sectoral impacts corresponding to any vector of changes in final demand. Exogenous shocks treated as changes in final demand are fed through an input-output model to generate sectoral effects that are then introduced into the spatial allocation model.

An early 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 since been applied to other Los Angeles metropolitan-area policy problems. Our work on Northridge earthquake business interruption effects uses SCPM1. That model is driven by reduced demand by damaged businesses, as ascertained in a survey of businesses.

The first model component is built upon the Regional Science Research Corporation 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 using Regional Purchase Coefficients (RPC); 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 was to adapt a Garin-Lowry style model for spatially allocating the induced impacts generated by the input-output model. 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-from-services-to-home matrix that is more restrictively described as a "journey-to-shop" matrix in the Garin-Lowry model.

The journey-from-services-to-home matrix includes any trip associated with a home based transaction other than the sale of labor to an employer. This includes retail trips and other transaction trips, but excludes nontransaction trips such as trips to visit friends and relatives. Data for the journey-from-services-to-home matrix includes all of the trips classified by the Southern
California Association of Governments as home-to-shop trips, and a subset of the trips classified as home-to-other and other-to-other trips.

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 using a journey-to-work matrix and from the residential site to the place of purchase or consumption through a journey-to-services matrix. See Appendix A for a further summary of SCPM1.

Incorporating the Garin-Lowry approach to spatial allocation makes the transportation flows in SCPM1 exogenous. They are also relatively aggregate, defined at the level of political jurisdictions. With no explicit representation of the transportation network, SCPM1 has no means to account for the economic impact of changes in transportation supply and demand. Earthquakes are likely to induce such changes.

2. APPROACH

In the present work, we focus on a hypothetical earthquake, a magnitude 7.1 event on the Elysian Park blind thrust fault. Figure 1 is a map of the Los Angeles metropolitan area described in terms of the transportation network.

FIGURE 1: The Los Angeles Metropolitan Area Transportation Network, Consisting of 19,601 Links and 1,534 Traffic Analysis Zones.

The circle includes Elysian Park and downtown Los Angeles. The Elysian Park fault runs East Southeast from the center of the circle. 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).

The building damage models in EPEDAT are based on ground motion, structural type, number of stories, and building use category. These models incorporate expert judgment and empirical damage data from previous earthquakes. The EPEDAT data for Los Angeles incorporate building inventory data and experience from previous disasters. The EPEDAT models do not include measures of construction quality. Detailed building inventory data on construction quality is generally nonexistent.

EPEDAT predicts, among other values, the lengths of time for which firms throughout the region will be nonoperational. This allows the calculation of exogenously prompted reductions in demand by these businesses. These are introduced into the interindustry model as reductions in final demand (Isard and Kuenne, 1953). Explicit treatment of the transportation network makes it possible to model the concurrent impact of transportation cost changes on the activity system, including reductions in regional network capacity resulting from large numbers of bridge failures.

Figure 2 summarizes our approach. Engineering models predict damage to transportation structures by location for the Elysian Park scenario. EPEDAT predicts spatial loss of industrial function. The I-O model translates this production shock into direct, indirect, and induced costs, and the indirect and induced costs are spatially allocated in terms consistent with the endogenous transportation behaviors of firms and household.

Implementing this approach is a data intensive effort that builds on the data resources assembled for SCPM1. SCPM2 results are computed at the level of the Southern California Association of Governments’ (SCAG) 1,527 traffic analysis zones, and then aggregated to the level of the 308 political jurisdictions defined for SCPM1. These jurisdictional boundaries routinely cross traffic analysis zones. Results for traffic analysis zones crossed by jurisdictional boundaries are allocated in proportion to area. Like SCPM1, SCPM2 aggregates to 17 the 515 sectors represented in the Regional Science Research Corporation’s PC I-O model Version 7 (Stevens, 1996) based on the work of Stevens, Treyz, and Lahr (1983). This research extended SCPM1 by treating the transportation network explicitly, endogenizing otherwise exogenous Garin-Lowry style matrices describing the travel behavior of households, achieving consistency across network costs and origin-destination requirements. SCPM2 makes distance decay and congestion functions explicit. This allows us to endogenize the spatial allocation of indirect and induced economic losses by endogenizing choices of
FIGURE 2: Summary of the Southern California Planning Model-2 (SCPM2).
route and destination. This better allocates indirect and induced economic losses over zones in response to direct earthquake losses to industrial and transportation capacity.

Establishing a Baseline

Our goal is to model the effects of earthquakes on industrial capacity and system-wide transportation demand and supply. As far as possible we also measure the economic impacts associated with both of these effects. Our first step is to compute a pre-earthquake baseline that is consistent with respect to equilibrium network costs, network flows, and interzonal flows and origin-destination requirements.

SCPM1 includes work and shopping (including service) trips, but not other nonwork travel and freight flows. The SCAG origin-destination data includes requirements for work and nonwork 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 interzonal flows associated with the regional transportation network in terms of flows between SCPM zones.

Each element in the SCPM1 journey-from home to work matrix JHW 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 services-to-home matrix JSH describes the proportion of purchasers residing in zone $i$ who transact for services in zone $j$ relative to total to the total number of purchasers transacting in zone $j$. The SCPM1 JHW matrix is based on spatial distributions extracted from the Census Transportation Planning Package (CTPP) made available to SCAG by the U.S. Bureau of Transportation Statistics (U.S. Department of Transportation, 1994). The SCPM1 version of the JSH matrix is the result of a gravity model estimation. In the SCPM2 extension developed in this research, the elements of the JHW and JSH 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 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 is 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. Consequently,
we also rely on 1996 international export sales for the five-county area (U.S. Bureau of the Census, 1997). These data are tabulated in the Metro Area Exporter Location (EL) file (www.ita.doc.gov).

Given the SCPM input-output relationships describing input requirements per unit of output, and given baseline jobs by economic sector and zone from the CTPP, the next step is to compute the total requirements of output \( i \) in zone \( z \)

\[
D_i^z = \sum_j a_{i,j} X_j^z + \text{sector } i \text{ shipments to zone } z \text{ from transshipment zones (imports) and from other zones to accommodate local final demand not associated with households}
\]

where \( X_j^z \) = the total output of commodity \( j \) in zone \( z \) given base year employment in sector \( j \) and zone \( z \),

and

\[
a_{i,j} = \text{is the } i,j\text{th element of the matrix of value demand coefficients for the (open) input-output model } A. \text{ This is the flow from } i \text{ to } j \text{ per unit output of } j.
\]

The first term on the right-hand side of Equation (1) accounts for interindustry shipments out of all zones by aggregate freight sector \( i \). This summation applies to the open input-output model so \( D_i^z \) 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. \( D_i^z \) is the total flow of commodity \( i \) supplied from everywhere to all nonfinal demand activities in zone \( z \).

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

\[
O_i^z = \sum_j b_{i,j} X_i^z + \text{sector } i \text{ shipments to transshipment zones from zone } z \text{ to accommodate nonlocal final demand (exports) and to other zones to accommodate local final demand not associated with households}
\]

where \( X_i^z \) = the total output of commodity \( i \) in zone \( z \) given base year employment in sector \( i \) and zone \( z \),

and

\[
b_{i,j} = \text{is the } i,j\text{th element of the matrix of value supply coefficients for the (open) input-output model } B. \text{ This is the flow from } i \text{ to } j \text{ per unit output of } i.
\]

The first term on the right-hand side of Equation (2) accounts for interindustry shipments out of zone \( z \) by aggregate freight sector \( i \). Like \( D_i^z \), \( O_i^z \) excludes most

shipments to households. As in the case of Equation (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 \( i \) and originating in zone \( z \) and value flows \( D^z_i \) demanded from activity \( i \) and terminating in 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 \( O^z_i \) dollar values to truckload equivalents. The CFS describes freight flows in terms of dollars per ton for the major industrial sectors. The 1992 census of transportation (U.S. Bureau of the Census, 1993) describes tons per truck. This permits calculation of a coefficient \( \eta_i \) relating the value of shipments to zonal transportation requirements, typically passenger car units (PCU)

\[
(3) \quad P^r_i = \eta_i O^z_i
\]

= trip production of commodity \( i \) in origin zone \( z = r \)

and

\[
(4) \quad A^s_i = \eta_i D^z_i
\]

= trip attraction of commodity \( i \) to destination zone \( z = s \)

Based on available network equilibrium costs \( c^x_{SCAG} \) and the trip production and attraction vectors determined previously, we calibrate thirteen separate spatial interaction models. These include the four classes of commodity flows listed above and nine flows involving people: home-to-work, work-to-home, home-to-shop, shop-to-home, home-to-other, other-to-home, work-to-other, other-to-work, and other-to-other. We estimate each of these thirteen matrices of interzonal flows separately, but in response to a common measure of network equilibrium costs. The structure of interzonal 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 is the estimation of distance decay parameters (Wilson, 1970). These distance decay parameters are used to predict travel demand following an earthquake. Once estimated, the home-to-work matrix is converted to the \( JHW \) matrix by striking proportions in columns, that is, relative to the total number of trips terminating in zone \( j \). The home-to-shop matrix is added to a subset of flows from the home-to-other and other-to-other matrices; and then converted to be \( JSH \) matrix, also by striking proportions in columns.

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

\[
\text{Min}_{\beta_i} \sum_r P_i^r(\beta_i) \ln \left( P_i^r \right) - \sum_r P_i^r(\beta_i) \ln \left[ P_i^r(\beta_i) \right]
\]

where

- \( \beta_i \) = distance decay coefficient for sector \( i \);
- \( P_i^r(\beta_i) \) = estimated trip production of commodity \( i \) in origin zone \( r \);
- \( \sum_s A_i^s \left[ B_i^r \exp(-\beta_i c^{r,s}) / \sum_r B_i^r \exp(-\beta_i c^{r,s}) \right] \)
- \( c^{r,s} \) = 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 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 \( \beta_i \) is adjusted to move the estimated values \( P_i^r(\beta_i) \) toward the target values \( P_i^r \).

We have more information about people flows, namely, 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

\[
t_i^{r,s}(3) = P_i^r A_i^s \left[ B_i^r H_i^s \beta_{0,i} \exp(-\beta_{1,i} c^{r,s}) c^{r,s}(\beta_{2,i}) \right]
\]

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 \( r \)

\[
= \left[ \sum_s A_i^s H_i^s \beta_{0,i} \exp(-\beta_{1,i} c^{r,s}) \right]^{-1}
\]

and

\[ H_i^s = \text{constant specific to sector } i \text{ and origin zone } rs \]

\[ = \left[ \sum_r P_i^r B_i^r \exp(-\beta_{1r}c^{r,s}) c^{r,s(-\beta_{2r})} \right]^{-1} \]

Calibration is accomplished by adjusting the vector \( \beta \) to match the observed travel distribution, which in turn depends on the observed flows \( t_i^{r,s} \) and the equilibrium network costs \( c^{r,s} \).

In all cases, equilibrium transportation costs \( c^{r,s} \) are initialized as \( c^{r,s}_{SCAG} \), based on estimated link flows and costs provided by the Southern California Association of Governments. The parameters that minimize Equation (5) and match the travel time distributions for observed flows also produce 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 of distance decay parameters \( \beta \) are 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 \( t_i^{r,s} \).

**Status Quo: Earthquake Impacts Without Mitigation**

The information needed to model the baseline with the internal consistency described here is 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 reduces demands imposed on the network. The building fragility curve analysis provided by EPEDAT and the bridge performance models ascribe consistent losses of both types to particular earthquake scenarios. 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.

3. AN APPLICATION: THE ELYSIAN PARK SCENARIO EARTHQUAKE

SCPM2 is 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. Although 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 event varies in depth from 11 to 16 kilometers below the surface. The surface projection of this source includes a broad, densely populated area of central Los Angeles County, including downtown Los Angeles.

**Bridge Fragility Curves**

Bridge fragility curves (Shinozuka, 1998; Shinozuka et al., 2000) give the probability distribution of bridge damage states conditioned by bridge type and earthquake event in the case the Elysian Park scenario. These damage states are defined in terms of a bridge damage index (BDI) ranging from zero (no damage) to unity (collapse). See Table 1.

The qualitative labels for bridge damage states are standard in the earthquake engineering field, but the functionality of a damaged bridge remains subjective. Yet, the earthquake and transportation engineering literatures remain silent on the question of how to translate qualitative characterizations such as "moderate damage" or "severe damage" into traffic capacity. A moderately damaged bridge might well be used before the bridge is repaired or replaced by, for example, restricting its use to automobiles, restricting the right of way to the least damaged portions of the bridge deck, suppressing vibrations by instituting very low speed limits for larger vehicles, metering access to the bridge to ensure low density volumes, or temporarily reinforcing the bridge. However, operations personnel from several State Departments of Transportation (DOTs) indicate that the liability and safety risks associated with extracting service from a damaged bridge suppresses the likelihood that these options would be implemented. If there is a substantive risk of injury or death from post earthquake failures, the current operational perspective is that the bridge should be closed. The California Department of Transportation appears somewhat more risk tolerant in this respect than DOTs in the midwest, but we conclude that this reflects the California perspective that earthquakes are not rare events, and a particularly sophisticated view of the importance of network management. Still, from a network management perspective the key operational question for all State DOTs is "At what bridge damage index value should bridge closure occur?" Our approach makes it possible to systematically investigate the cost implications of alternative bridge closure criteria.

<table>
<thead>
<tr>
<th>Bridge Damage State</th>
<th>Representative Bridge Damage Index (BDI)</th>
<th>Approximate Interval of Bridge Damage Index Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Damage</td>
<td>0.000</td>
<td>0.000–0.050</td>
</tr>
<tr>
<td>Minor Damage</td>
<td>0.100</td>
<td>0.050–0.200</td>
</tr>
<tr>
<td>Moderate Damage</td>
<td>0.300</td>
<td>0.200–0.525</td>
</tr>
<tr>
<td>Major Damage</td>
<td>0.750</td>
<td>0.525–0.875</td>
</tr>
<tr>
<td>Collapse</td>
<td>1.000</td>
<td>0.875–1.000</td>
</tr>
</tbody>
</table>

Note: *Cho et al. (1999).*

The approximate midpoints of the bridge damage index intervals associated with moderate and severe damage states are 0.30 and 0.75, respectively. We treat 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 will close moderately damaged structures to traffic, including bridges with a damage index \( \geq 0.30 \). This will increase delay and other transportation costs. A less risk averse policy emphasizing an emergency focus on maintaining regional economic function will leave moderately damaged structures open, closing only bridges with a damage index \( \geq 0.75 \). No authority will 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 is 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 relate 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 dollars and 36.2 billion dollars for the Elysian Park event. If building contents are included, property damage is estimated at 33.9 dollars to 56.6 billion dollars. 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 provides changes in output and employment for 17 sectors across 308 zones. This is an iterative calculation. Direct changes are exogenous and already spatially identified. SCPM2 allocates indirect and induced changes in a way that respects both observed travel behavior and new network costs. A core contribution of this research is the ability to more completely endogenize submetropolitan freight and passengers flows and destinations. In this case nine classes of passenger flows are combined with four classes of freight and loaded on a common network. Details of this procedure appear in Appendix B.

**Results for the Elysian Park Scenario Earthquake**

**Aggregate results.** Bridge damage results are 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 dimension 2,810 bridges, each assigned a BDI value. The alternative bridge closure criteria (BDI $\geq 0.30$, BDI $\geq 0.75$) 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. We implement an improved version of the Frank-Wolfe algorithm that relies on an application of the dual simplex method to complete shortest path calculations. Preliminary comparisons with commercial codes indicate substantial computational advantage with respect to large scale network flow estimates. Yet, it is still computationally infeasible to exhaustively investigate each network state represented in these distributions. Instead, we select representative members of each. The 200 simulations are rank ordered in terms of the baseline vehicle-miles that would otherwise be traveled across the damaged links. This rank ordering makes it possible to identify those simulations that are maximally disruptive with respect to baseline transportation flows, and representative in a median sense. Figures 3 and 4 identify maximal and median outcomes, respectively, for a conservative, safety-oriented bridge closure criterion of BDI $\geq 0.3$.

FIGURE 3: Closed Freeway Segments, BDI $\geq 0.75$, Maximum of 200 Simulations.

An example of preliminary simulation results describing the full costs of a magnitude 7.1 Elysian Park event are summarized in Table 2. Row A reflects the midpoint of the range of structure damage predicted by EPEDAT, 45.25 billion dollars including 29 billion dollars in structure losses. This is the unamortized replacement (or repair) cost of buildings and contents. This value excludes the cost of replacing bridges. Row B is the sum of direct, indirect, and induced losses computed by the I-O model of the five-county, Los Angeles metropolitan area. This sum is 46.7 billion dollars. These aggregate values are identical across all other simulations (Cho et al., 1999). These costs are a cumulative impact over one year of economic activity. Row C summarizes the post-earthquake network equilibrium transportation costs in light of reduced production and reduced network capacity. These values vary across all simulations. These costs are also cumulative over one year of economic activity. Table 2 corresponds to maximum simulated disruption of baseline transportation combined with a conservative, safety-oriented bridge closure criterion. This results in a substantial reduction in transportation network capacity, and an associated increase in transportation costs of almost 43 billion dollars. The full costs of the earthquake are estimated to be almost 135 billion dollars, close to 20 percent of Gross Regional Product (GRP), although direct (business interruption) costs account for about six percent. In this case, transportation costs account for a little less than one-third of the full cost of the earthquake. The full costs for the

FIGURE 4: Closed Freeway Segments, BDI ≥ 0.30, Median of 200 Simulations.

TABLE 2: Total Loss ($Billions): Elysian Park Magnitude 7.1 Earthquake, Maximum Simulated Disruption to Baseline Transportation (Closure at BDI ≥ 0.30)

<table>
<thead>
<tr>
<th>Loss Type</th>
<th>Baseline</th>
<th>Elysian Park Scenario:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Conservative Bridge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Closure Criterion</td>
</tr>
<tr>
<td>A Structure Loss&lt;sup&gt;a&lt;/sup&gt;</td>
<td>$45.250 billion (33.5 percent of total)</td>
<td></td>
</tr>
<tr>
<td>Business Loss</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Loss&lt;sup&gt;b&lt;/sup&gt;</td>
<td>28.155</td>
<td></td>
</tr>
<tr>
<td>Indirect Loss&lt;sup&gt;c&lt;/sup&gt;</td>
<td>9.627</td>
<td></td>
</tr>
<tr>
<td>Induced Loss&lt;sup&gt;d&lt;/sup&gt;</td>
<td>8.955</td>
<td></td>
</tr>
<tr>
<td>B Business Loss Subtotal</td>
<td>46.737 billion (34.6 percent of total)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network Costs&lt;sup&gt;e&lt;/sup&gt;</th>
<th>PCU Minutes</th>
<th>$ Billions</th>
<th>PCU Minutes</th>
<th>$ Billions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Travel Cost</td>
<td>85,936,813.</td>
<td>21.290</td>
<td>225,830,486.</td>
<td>56.300</td>
</tr>
<tr>
<td>Freight Cost</td>
<td>10,298,781.</td>
<td>4.550</td>
<td>28,285,954.</td>
<td>12.495</td>
</tr>
<tr>
<td>Total Travel Cost</td>
<td>95,695,594.</td>
<td>25.839</td>
<td>254,116,440.</td>
<td>68.795</td>
</tr>
</tbody>
</table>

Network Loss = Δ Network Costs

<table>
<thead>
<tr>
<th>Loss Total = A + B + C</th>
<th>PCU Minutes</th>
<th>$ Billions</th>
</tr>
</thead>
<tbody>
<tr>
<td>140,433,673.</td>
<td>35.010</td>
<td></td>
</tr>
<tr>
<td>17,987,173.</td>
<td>7.946</td>
<td></td>
</tr>
<tr>
<td>158,420,846.</td>
<td>42.956</td>
<td></td>
</tr>
<tr>
<td>(31.8 percent of total)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Loss Total = A + B + C

$134.943 billion

Notes: <sup>a</sup>Midpoint of the range of structure damage predicted by EPEDAT, EQE International.<br><sup>b</sup>EPEDAT<br><sup>c</sup>RSRI Model.<br><sup>d</sup>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.<br><sup>e</sup>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 dollars per hour, and 35 dollars per hr for freight.

The median case in 200 simulations are 102.332 billion dollars. Slightly more than ten percent of the median value consists of increased travel costs.

One way to interpret the full cost of the earthquake is as the true cost of damage to economic stocks, expressed as the sum of replacement and repair costs and the net present value of future losses due to diminished production and transportation stocks. The loss-of-function curves used in this research describe production capacity over a one-year period following the earthquake. Production capacity is predicted by EPEDAT to approach pre-earthquake levels within six months. Restoration of transportation network capacity is less well accounted for at this point. Bridges are 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 accommodated to further refine these preliminary results. Damage to Los Angeles freeways was repaired very quickly after the Northridge earthquake. Repairs in the San Francisco Bay Area took significantly longer than one year following the Loma Prieta earthquake. State DOT officials provide very different expert estimates of the time required for repair following extensive damage.

*Summary of spatially disaggregated results.* SCPM2 provides unprecedented disaggregation of economic impacts over metropolitan space. Tabular results for this research and corresponding maps are available on our website (http://www.usc.edu/schools/research/research2.html). A summary of the disaggregate results indicates the following:

Nonstructural direct economic (business interruption) losses are 28.2 billion dollars, or 3.65 percent of the I-O model GRP baseline. Most of these losses are in Los Angeles County, where the finance, insurance and real estate (FIRE) sector account for 15 percent of the total losses.

The region's five largest cities (Los Angeles, Long Beach, Anaheim, Santa Ana, and Irvine) suffer the largest business interruption losses in absolute terms. This is as expected, that is, the largest cities are likely to accrue the largest losses.

Of the twenty cities (subareas in the case of the City of Los Angeles) that suffer the greatest proportionate business interruption impacts, the five cities and subareas most heavily affected lose slightly less than six percent of their GRP (5.46 to 5.83 percent). The twenty proportionally hardest hit cities and subregions are located mainly in the central and east-central areas of the region. Nine of the top twenty are subareas of the city of Los Angeles, mostly located toward the east. The only westside cities among the top twenty are Beverly Hills and West Hollywood.

Regional, nonstructural indirect economic losses are 9.6 billion dollars, accruing mostly in Los Angeles County. Regional induced economic losses are 8.9 billion dollars, also mostly to Los Angeles county. Total economic losses given no network damage are 46.8 billion dollars, or 6.05 percent of GRP. This implies an overall multiplier between direct and total impacts of 1.66. Most regional indirect economic losses are in the manufacturing (nondurable) and FIRE sectors. Most regional induced economic losses are in the same sectors, but the FIRE sector is more heavily affected than the nondurable manufacturing sector.

Corresponding results are calculated for other representative bridge-closure simulations. All of these results include 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
source of local impacts. These costs are more difficult to disaggregate. There is insufficient information to reliably allocate these transportation costs to economic sectors, but these costs can be geographically distributed to traffic origins and destinations. These new network costs may also influence the distribution of indirect and induced economic losses through the distance decay relationship between travel cost and destination choice. However, 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 affect total travel cost and route choice. A comparison of our simulations indicates 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.

4. CONCLUSIONS

Summary of Results

These research results permit us to 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. This approach has three elements; specifying an integrated model, assembling data from disparate sources, and achieving computability. Our results are preliminary, and we continue to pursue improvements in all three dimensions. Our estimate that the full cost of an Elysian Park earthquake will account for 20 percent of GRP is plausible in light of the available literature. Structure losses account for approximately one-third of this total. Modeling business interruption costs is essential for estimating full regional economic losses.

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 effect 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.
Research Extensions

Policy tests: earthquake impacts with alternative mitigation measures. 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 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, city council districts. If all politics are indeed local, then results like this are critically important to policy implementation.

However, these sorts of comparisons remain difficult. SCPM2 provides a good starting point. SCPM2 can determine a distribution of costs associated with a given earthquake scenario. More fundamental information is needed to apply SCPM2 to policy evaluation. Bridge fragility curves have been estimated for unretrofitted structures, but are not available for retrofitted facilities. Consequently the additional post-earthquake transportation capacity that would be made available by retrofit programs is difficult to model.

Even as improved engineering models are made available, rational prioritization of facilities for retrofit will remain a challenge. Retrofit, repair, and reconstruction options are probably best described as a special case of the network design problem, and large-scale network design problems are difficult. SCPM2 makes it possible to model the system states associated with conventional attacks on the network design problem, but even our most efficient computing procedures are too expensive to allow the problem to be addressed optimally. Further, retrofit programs do not consist of projects dedicated to individual bridges. Large-scale bridge retrofit and reconstruction programs involved defining projects consisting of several proximate facilities bundled to reduce equipment and traffic diversion costs.

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

First, this application of SCPM2 remains incomplete. The loss-of-function curves apply only to production activities. The impact on households, that is, 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.

Second, 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.

Third, travelers may 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 will be removed from these results, which will intensify changes in the geographic distribution of activities and losses.

In addition to the obvious data difficulties, there are a variety of inevitable theoretical 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 in this procedure. Input-output approaches emphasize backward linkages but ignore forward linkages. The reduced demand associated with damaged industrial facilities is included, but the consequences of constraints on industrial capacity are overlooked. We did 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.

Treating the Los Angeles metropolitan region in isolation from the rest of the world inevitably distorts the local economic impact of a Los Angeles earthquake. Cochrane (1997) and others suggested that regions affected by earthquakes are likely to increase their imports to make up for local shortfalls, and undamaged firms within the region may seek export markets outside the region if local demands are reduced. SCPM2's I-O framework does not accommodate these adjustments well, and these may be important, particularly with respect to transportation costs. While interregional import and export changes will reduce production losses, these interregional changes also tend to increase demand for transportation, and intensify transportation costs.

Perhaps most importantly, the interindustry core of SCPM2 does not account for the role of price changes. Price adjustments are crucial resource allocation mechanisms, especially in areas afflicted by natural disasters. In addition to addressing the points listed above, our current research activity will extend SCPM2 to account for endogenous price adjustments.

REFERENCES


APPENDIX A

Southern California Planning Model Version 1 (SCPM1)

The generic structure of SCPM1 is summarized as follows. First, beginning with a vector of final demands, \( \mathbf{v}(d) \), total outputs from the open and closed input-output (I-O) models are calculated as

\[
\mathbf{v}(o) = (I - A_o)^{-1} \mathbf{v}(d)
\]

and

\[
\mathbf{v}(c') = (I - A_c)^{-1} \mathbf{v}(d)
\]

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

\[
\mathbf{v}(c) = \mathbf{v}(d) + \mathbf{v}(i) + \mathbf{v}(u) \quad (17 \times 1)
\]

and

\[
\mathbf{v}(u) = \mathbf{v}(c) - \mathbf{v}(o)
\]

Equation (A2) is the spatial counterpart to Equation (A1)

\[ Z(c) = Z(d) + Z(i) + Z(u) \quad (308 \times 17) \]

where in each case \( Z(\bullet) \) 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

\[ Z(i) = P \text{Diag}(v(i)) \]

where \( P \) is a \((308 \times 17)\) matrix indicating the proportion of employees in each zone. The “Diag” operator diagonalizes the indicated vector into a \((17 \times 17)\) matrix.

The spatial allocation of induced impacts is somewhat more involved because the induced output must be traced via household expenditure patterns. Two separate origin – destination matrixes are employed, journey-from-services-to-home \( JSH \) and journey-from-home-to-work \( JHW \) based on spatial distributions extracted from the Census Transportation Planning Package (CTPP). 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

\[ Z(u) = JSH \times JHW \times P \times \text{Diag}(v(u)) \quad (308 \times 308)^2 \times (308 \times 17) \times (17 \times 17) \]

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

**APPENDIX B**

*Endogenizing Transportation Flows: Southern California Planning Model Version 2 (SCPM2)*

SCPM2 is initialized by allocating indirect impacts to zones in proportion to baseline data by applying a modified version of SCPM1. SCPM1 relies on the proportion of workers in each traffic analysis zone to establish the spatial distribution of economic activities. The modified version of SCPM1 applied here relies instead on a \(1527 \times 17\) matrix of indices constructed from economic flows into and out of each traffic analysis zone, the elements of which are initialized as

\[ F_i^x = \left[ O_i^x + D_i^x / \sum_z (O_i^z + D_i^z) \right] \]

where \( O_i^x \) and \( D_i^x \) 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 journey-from-home-to-work $JHW$ and journey-from-services-to-home $JSH$ matrices, a matrix $V(d)$ of direct impacts by sector and municipality from EPEDAT, disaggregated using 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 iterative 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

$$k^0D_i^z = D_i^z$$
$$k^0O_i^z = O_i^z$$
$$k^0F_i^z = F_i^z$$
$$k^0V(i) = F^{Diag}[v(i)]$$

and

(A3) \[ k^0V(u) = k^0JSH^T \times k^0JHW \times k^0F \times \text{Diag}[v(u)] \]

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

(A4) \[ k^zV = k^zV(d)^z + k^zV(i)^z + k^zV(u)^z \]

Unlike the corresponding elements of SCPM1, the matrices $JSH$, $JHW$, 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

$$\Delta^kD_i^z = \sum_j a_{i,j}^kV_j^z$$
$$\Delta^kO_i^z = \sum_j b_{i,j}^kV_i^z$$

These changes represent decrements in economic activity due to impact of the earthquake. They are subtracted from baseline values. Update $k^zD_i^z$ and $k^zO_i^z$ by defining

$$k^+1O_i^z = k^0O_i^z - \Delta^kO_i^z$$

and

$$k^+1D_i^z = k^0D_i^z - \Delta^kD_i^z$$

Update $k^+F_{i}^z$ by defining

$$k^+F_{i}^z = \left[ k^+O_{i}^z + k^+D_{i}^z \right] / \sum_{z} \left( k^+O_{i}^z + k^+D_{i}^z \right)$$

Convert these updated values $k^+D_{i}^z$ and $k^+O_{i}^z$ to marginal distributions of trip productions and attractions in PCUs

$$k^+P_{i}^r = \eta_i \times k^+O_{i}^z$$

and

$$k^+A_{i}^s = \eta_i \times k^+D_{i}^z$$

In SCPM1, the network is not explicit and trip making is exogenous. In SCPM2, the trip interchange matrices are adjusted subiteratively. The entries of the thirteen interchange matrices describing four classes of freight flows and nine passenger trip types are determined by applying the baseline gravity model coefficients and network costs to the set of updated trip production and attraction elements $k^+P_{i}^r$ and $k^+A_{i}^s$. In the case of freight flows

$$t_{i}^{r,s} = A_{i}^{s} \left[ B_{i}^{r} \exp\left(-\beta_{i,c^{r,s}}\right) / \sum_{r} B_{i}^{r} \exp\left(-\beta_{i,c^{r,s}}\right) \right]$$

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

$$t_{i}^{r,s} = P_{i}^{r} A_{i}^{s} \left[ B_{i}^{r} H_{i}^{s} \beta_{0,i} \exp\left(-\beta_{1,i,c^{r,s}}\right) c^{r,s}(\beta_{2,i}) \right]$$

Collectively, these interzonal 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 $k^+JHW$ and $k^+JSH$, which, along with $k^+F$, update $k^+V(i)$ to $k^+V(i)$ via Equation (A3) and $k^+V(u)$ to $k^+V(u)$ via Equation (A4).