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Transportation Research Part A 39 (2005) 849–860

TRANSPORTATION
RESEARCH
PART A

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Assessment of economic impacts from unexpected events with an interregional commodity flow and multimodal transportation network model

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Received in revised form 3 August 2004

Abstract

Loss and damage caused by unscheduled events, especially earthquakes, have sudden and significant impacts not only on the region's economy where the event occurs but also on other regions. The New Madrid Seismic Zone, located in the center of the United States, could have great impacts on economic activities related to this area, if a major earthquake occurred. Based on the 1993 US Commodity Flow Survey [US Commodity Flow Survey, 1993. Available from: <http://www.bts.gov/ntda/cfs/prod.html>], more than 42% of total commodity flows in the US are related to the greater Midwest, which includes the New Madrid Seismic Zone. If a catastrophic earthquake occurred in this area, the indirect damages could spread far beyond the region, and could have sizable impacts on other regions. A model of interregional commodity flows, incorporating regional input–output relationships, and the corresponding transportation network flows, was applied to assess the economic impacts of such an unexpected event. The economic impacts from the event are described for three hypothetical scenarios, analyzing the magnitude and the extent of the direct and indirect impacts. These analytical results may be used to propose strategic management of the recovery and reconstruction efforts after the event.

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0965-8564/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tra.2005.02.006

Keywords: Economic impacts on networks; Earthquake impact on networks; Commodity flow modelling; Combined input–output with network modelling

1. Introduction

The loss and damage caused by unexpected events, such as earthquakes, floods and other major natural disasters, have sudden and significant impacts on the region's economy where the event occurred. The impacts of the damages to production facilities and lifelines may also spread across boundaries of several regions through import–export relationships, and bring serious economic impacts to other regions. These economic impacts stem not only from the loss and damage, but also from the recovery and reconstruction activities. To recover and reconstruct the facilities and lifelines damaged from unexpected events through investment or government financial aid, both direct and indirect economic impacts from the events need to be measured in a regional and interregional context. Direct economic impact is the direct change of production and demand due to the disruption of production facilities and lifelines from an unexpected event; indirect economic impact is the change in other sectors brought about by the change of a sector through input–output relationships.

About 42% of total commodity flows in the United States are related to the greater Midwest, which includes the New Madrid Seismic Zone located near the center of the country. The Midwestern economy, including the states of Illinois, Indiana, Iowa, Kentucky, Michigan, Missouri, Ohio, Tennessee, and West Virginia, is probably best known for producing manufactured goods and agricultural products. What is less known is that the interstate trade within the Midwest is quite large. According to Kim et al. (2002) who analyzed commodity flows based on the 1993 Commodity Flow Survey data, nearly 40% of the aggregated outflows (exports) from the nine Midwest states go to other Midwest states while about 45% of the inflows (imports) are derived from the same region. The total volume of commodity trade among these nine states in 1993 was $417 billion, a value that exceeded trade of all commodities and services for the three members of NAFTA (US, Canada, and Mexico).

If a catastrophic earthquake were to occur in the New Madrid Seismic Zone located near Memphis, Tennessee, where the largest earthquakes in the history of the United States took place during the winter of 1811–12, it could damage the transportation network and production facilities within the entire Midwest. The indirect impacts from such an event would spread far beyond the Midwest region through import–export relationships and would have sizable impacts in other regions. The analysis of commodity flows among the Midwest states and the estimation of interregional effects through the trade relationship are crucial to the evaluation of indirect impact from such an event.

This paper presents a hypothetical assessment of the direct and indirect impacts of an earthquake in the New Madrid Seismic Zone. To estimate and evaluate the economic impacts from a catastrophic earthquake in regional and national context, a model of interregional commodity flows, incorporating regional input–output relationships, and corresponding transportation network flows, was applied to highway and railway networks, using an interregional commodity flow model developed by Ham et al. (2005). The model integrates the conventional four step-process of travel forecasting (trip generation, trip distribution, mode choice and route choice) into a single combined model.

Related research on the economic impacts of unscheduled events has been conducted in recent years, often as part of the National Science Foundation's earthquake research program. Cho et al. (2001) developed an integrated transportation network and regional economic model of the Los Angeles economy. They integrated four models including bridge and other structure performance models, transportation network models, spatial allocation models, and input–output models. Brookshire et al. (1997) described the mechanism of HAZUS (an earthquake loss estimation methodology), which includes a Direct Economic Loss Module as a part of the whole system. Chang (1998) developed a direct economic impact methodology for evaluating the direct economic losses caused by lifeline disruption in an urban area.

Cochrane (1997) developed and applied a supply shock model (part of the National Institute of Building Standards model) focusing on the effects of production constraints and the potential for reallocating surviving capacity. Surviving production is also reallocated according to the input–output direct input coefficient matrix until all sector excess supplies and demands are eliminated. Rose et al. (1997) and Rose and Benavides (1998) constructed and applied a supply shock model for estimating the regional economic losses from a disruption of electricity services in the New Madrid Seismic Zone, using the input–output table for Shelby County, Tennessee. The supply shock model estimates the new final demand vectors after the event to reflect direct damages. Okuyama et al. (1997) applied Miyazawa's (1976) extended input–output formulation to the Kobe earthquake, finding that the pattern of impacts on income changes across the regions differed notably from those of gross output changes. Finally, Cole (1998) combined the Social Accounting Matrix approach with GIS in his exploratory approach to explain the economic impact from the earthquake.

The remainder of this paper is organized in the following way. First, the model is described in a general way, summarizing the technical description in Ham et al. (2005). Next, the data used to implement and validate the model are presented, with a few illustrative results. Finally, the model is applied to estimate the effect of three earthquake scenarios and their combination. Again, only highly summarized results are presented.

2. Interregional commodity flow model

The interregional commodity flow model consists of a multi-regional input–output model of 13 industrial sectors producing a like number of commodities, and distributed over seven regions. The model is based on the classic commodity flow model originally proposed by Leontief and Strout (1963) and formalized and extended by Wilson (1970). This interregional commodity flow model is integrated with a transportation network model to estimate transportation network commodity flows by sector and mode. These interregional, modal flows are allocated to routes and links according to a simple least cost criterion, minimum distance traveled. The model is formulated as a constrained optimization problem, solved by a partial linearization algorithm, and estimated with 1993 commodity flow data.

The model formulation was motivated by the following scenario. A large region or nation is divided into several (say 5–10) economic/political regions (e.g. states). Each region comprises one or more urban regions as well as rural agricultural, forestry or mining activities. Regional economic models encompassing both input–output and econometric relationships are presumed to be available for each region, describing the relationships between regional production by sector for regional consumption, investment and government, as well as exports to other regions. We wish to augment the descriptions and forecasts provided by these regional models with a forecast of the interregional commodity flows by sector and mode, and the associated vehicle flows placed on the interregional transportation system. Depicting these interregional relationships not only helps to understand the implications of regional growth for transportation investment, but also improve the validity of the regional models themselves.

In the following, we assume that each sector produces one aggregate commodity. Therefore, we use the terms sector and commodity interchangeably. The level of aggregation is 11 sectors/commodities plus the construction and service sectors which produce only for final demand. The classification of sectors is shown in Table 1.

Because each region consists of several urban areas, as well as rural areas, a reasonable representation of interregional commodity flows requires that the regions be subdivided into several subregions connected by a road and rail transportation networks. We presume that the regional production and final demands can be allocated to these subregions. For this purpose, we divided the entire USA into 36 analysis zones; 29 of these are located in the nine Midwestern states, as shown in Fig. 1.

Commodity flow data for the United States are collected periodically by the US Bureau of the Census in cooperation with the Bureau of Transportation Statistics, US Department of Transportation. Flow data are available by commodity between the 50 states and between somewhat smaller regional economic units called National Transportation Analysis Regions (NTAR). Interregional flows by mode are also available, but not by commodity.

A roadway network, consisting of interstate highways, and a railway network are shown in Figs. 2 and 3. The data for the transportation network, including highways and railways, were based on 1997 National Transportation Atlas Database (NTAD) of the United States Department of Transportation. To analyze the highway commodity flows, the interstate highway network was defined to consist of 167 nodes and 532 links. The nodes and links are defined as highway intersections and distances between highway intersections respectively.

Table 1
Sector definitions

Sector	Definitions
1	Agriculture, Forestry, and Fisheries
2	Mining
3	Construction
4	Food and Kindred Products
5	Chemicals and Allied Products
6	Primary Metals Industries
7	Fabricated Metal Products
8	Industrial Machinery and Equipment
9	Electronic and Electric Equipment
10	Transportation Equipment
11	Other Non-Durable Manufacturing
12	Other Durable Manufacturing
13	TCU, Services, and Government Enterprises

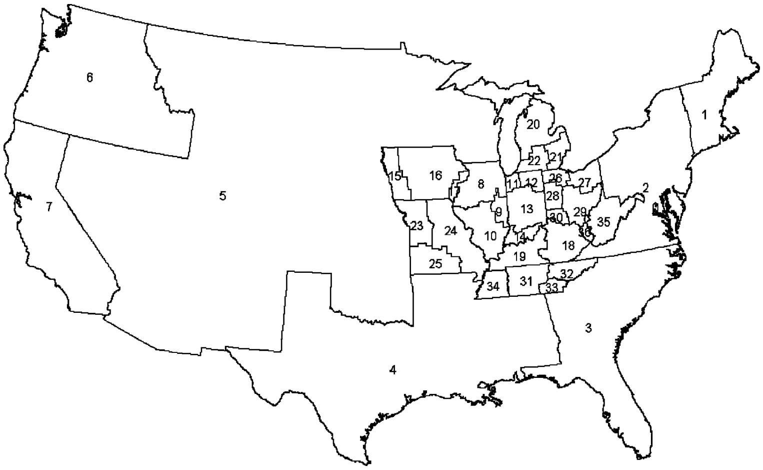

Fig. 1. Analysis regions.

Fig. 2. United States Interstate Highway System.

The railway network indicates main lines for the principal railroad companies as shown in Fig. 3. The railway network was abstracted into a spider or spanning network since it is too complicated to apply with the model. That is, the transportation facilities connecting each pair of adjacent subregions are represented by one link. The length of the link is the average distance between the subregional centroids. The capacity of a railway link is the number of main line tracks crossing the common boundary.

3. Validation of commodity flow estimates

Estimated commodity flows including originating shipments and terminating shipments, flow distributions among interregional and intraregional flows, shipments by mode, flows for highway

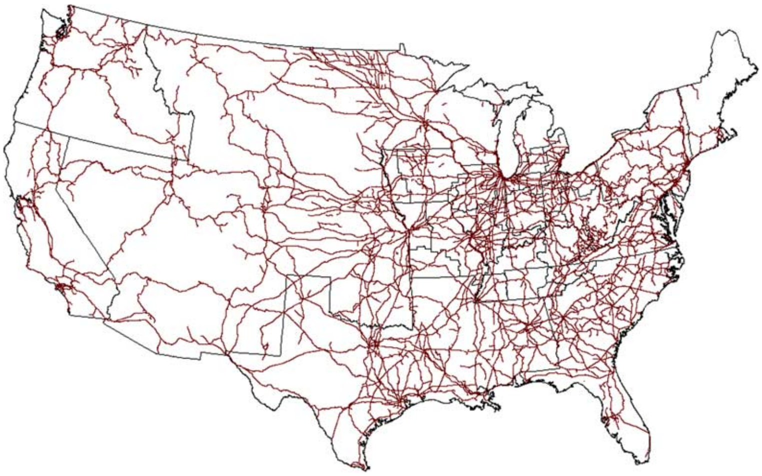

Fig. 3. United States Railway Network (main lines only).

and railway links, and total and mean shipment distances were obtained from the model solution. The commodity flows for sectors 3 (Construction) and 13 (Services) are excluded from the results in the following tables because they are assumed to be produced and consumed locally.

Total observed and estimated commodity flows by sector are compared in Table 2. Estimated shares for sectors 5, 6, 7, 9, and 12 differ little from the observed shares. The model also estimated the commodity flows using the highway and railway modes of transportation. As shown in Table 3, the mode share patterns between the observed and estimated are less than 10% for most sectors.

Table 4 shows the estimated commodity shipments by mode between the Midwest region and other regions. The mode shares from regions 6 and 7, farthest from the Midwest region, to the

Table 2
Annual commodity flow by sector

Sector	Observed[a]		Estimated		Difference of shares
	Flow (billion $)	Share (%)	Flow (billion $)	Share (%)	
1	121.6	2.9	264.1	6.7	−3.8
2	39.6	0.9	206.6	5.3	−4.4
4	814.7	19.2	521.1	13.3	5.9
5	460.7	10.8	398.6	10.2	0.6
6	185.2	4.4	153.5	3.9	0.5
7	211.0	5.0	149.1	3.8	1.2
8	338.9	8.0	200.0	5.1	2.9
9	323.4	7.6	340.3	8.7	−1.1
10	460.6	10.8	303.0	7.7	3.1
11	801.9	18.8	992.0	25.3	−6.4
12	496.7	11.7	396.8	10.1	1.6
Total	4254.3	100.0	3925.1	100.0	

[a] US Commodity Flow Survey (1993).

Table 3
Annual commodity flow by mode and sector

Sector	Highway				Railway			
	Flow (billion $)	Sector share (%)	Est. mode share[a]	Obs. mode share[b]	Flow (billion $)	Sector share (%)	Est. mode share[a]	Obs. mode share[b]
1	166.7	5.4	63.1	72.2	97.3	11.4	36.9	27.8
2	144.2	4.7	69.8	49.0	62.4	7.3	30.2	51.0
4	455.7	14.8	87.5	96.0	65.4	7.7	12.5	4.0
5	307.1	10.0	77.0	87.3	91.5	10.7	23.0	12.7
6	131.1	4.3	85.4	89.6	22.4	2.6	14.6	10.4
7	132.0	4.3	88.5	96.9	17.1	2.0	11.5	3.1
8	142.8	4.6	71.4	90.0	57.3	6.7	28.6	10.0
9	278.3	9.1	81.8	97.8	62.1	7.3	18.2	2.2
10	207.7	6.8	68.6	81.7	95.2	11.2	31.4	18.3
11	844.0	27.5	85.1	90.1	148.0	17.4	14.9	9.9
12	262.5	8.5	66.2	94.0	134.3	15.7	33.8	6.0
Total	3072.1	100.0	78.3	90.3	853.0	100.0	21.7	9.7

[a] Mode share for estimated commodity flow (%).

Table 4
Annual commodity flow by sector and mode between the midwest (MW) and other regions

From	To	Highway			Railway		
		Flow (billion $)	Regional share (%)	Mode share (%)	Flow (billion $)	Regional share (%)	Mode share (%)
1	MW	26.6	8.7	83.7	5.2	4.9	16.3
2	MW	94.2	30.8	85.2	16.3	15.4	14.8
3	MW	94.1	30.7	85.3	16.2	15.2	14.7
4	MW	42.2	13.8	80.5	10.2	9.6	19.5
5	MW	26.0	8.5	77.1	7.7	7.2	22.9
6	MW	2.3	0.7	26.0	6.5	6.1	74.0
7	MW	20.9	6.8	32.1	44.2	41.6	67.9
Total		306.3	100.0	74.2	106.3	100.0	25.8
MW	1	55.8	8.2	82.3	12.0	4.4	17.7
MW	2	204.2	29.8	87.2	29.9	11.0	12.8
MW	3	148.3	21.7	89.6	17.2	6.3	10.4
MW	4	120.9	17.7	80.5	29.4	10.7	19.5
MW	5	114.8	16.8	69.6	50.0	18.3	30.4
MW	6	9.8	1.4	24.1	30.8	11.3	75.9
MW	7	30.4	4.4	22.6	103.8	38.0	77.4
Total		684.2	100.0	71.5	273.2	100.0	28.5
MW	MW	922.2	na	90.2	100.5	na	9.8

na—not applicable.

Midwest region by railway are 74% and 68%, respectively. Likewise, the share by railway to those regions from the Midwest region are 76% and 77%, respectively, illustrating that the shipment modes are selected by the model based on the travel distance. In fact, distance is the most important variable in the cost functions for mode choice.

4. Scenario analyses

The model was applied to analyze the economic impacts of unexpected events, such as earthquakes, with hypothetical scenarios in the New Madrid Seismic Zone. Assuming a transportation network were damaged by an earthquake, interregional economic impacts on commodity flows in conjunction with input–output relationships can be estimated. As measures of the economic impacts, the mean shipment length and total commodity flows by mode were estimated from the model. Five scenarios, as shown in Fig. 4, were analyzed and evaluated. The highway network links related to the scenarios assumed to have been disrupted by a catastrophic event are:

A: Section of I-94 between Chicago, IL and Gary, IN.
B: Section of I-65 between Louisville, KY and Nashville, TN.
C: Section of I-40 between Little Rock, AR and Nashville, TN.
D: Combined sections of Scenarios B and C.
E: Combined sections of Scenarios A, B and C.

Interstate highway I-94 (Scenario A) is located at a substantial distance from the New Madrid Seismic Zone. The impacts due to the disruption of this section are evaluated because it is consid-

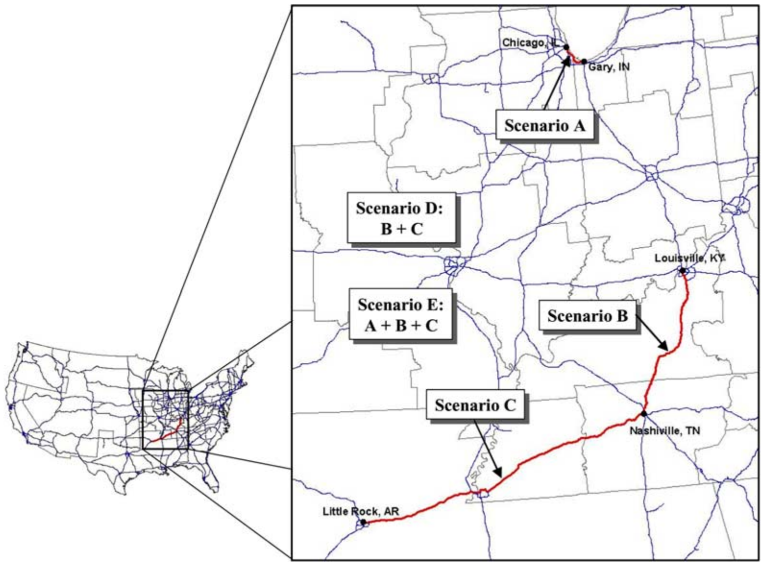

Fig. 4. Locations of the disrupted Highway Sections in Scenarios A–C.

ered to be the most heavily used highway by trucks in the United States. Interstate highway I-65 (Scenario B) and Interstate highway I-40 (Scenario C) are located near the New Madrid Seismic Zone within the Midwest region. Scenarios D and E, combinations of the first three situations, represent potential disruption of two or more sections of the interstate highway.

The measures estimated from the model without the event are compared with measures with the scenario events. Table 5 shows mean shipment lengths consistently increase for all scenarios due to disruptions of highway sections. For scenario A, the mean shipment lengths increase to 519.6 miles for truck, an increase of 15.1 miles, and 1181.1 miles for railway, an increase of 26.5 miles. The values estimated for Scenarios B and C also increase, but the impacts are smaller than for Scenario A. Thus, the model estimates agree with the conventional view that I-94 involves more trucking activities than I-65 in Scenario B and I-40 in Scenario C. The values measured on Scenario D and Scenario E are increased more than those of the previous scenarios due to the combination of the scenarios.

Although the mean shipment lengths increase at most 40 miles, these changes are significant since they are relative to the entire network. In particular, these impacts should be evaluated with other changes related to commodity flows, as shown in Table 6. These rates and values may be used as the information to mitigate possible damages before an earthquake, and strategies of recovery and reconstruction after an earthquake.

For these scenario conditions, the commodity flows are seen to be transferable. That is, when the highway shipment costs increase due to the disruption of the highway sections, some commodity flows using the highway shift to the railway with its lower shipment costs. In addition, under the same situation some commodities remain within the region rather than flowing to other regions. These phenomena in the model reflect the commodity flow patterns in the real world.

Table 6 shows changes in commodity flows due to the disruption of the highway sections for each scenario. In Scenario A, the total interregional commodity flows without the event were \$2,863.8 billion, which decrease to \$2,856.6 billion with the event. Interregional commodity flows of \$7.2 billion are transferred to intraregional commodity flows because of the increased shipment

Table 5
Increase in mean shipment length by mode for the five scenarios

Scenario/mode		Mean shipment length (miles)			
		Without event	With event	Increase	Relative change (%)
A	Highway	504.5	519.6	15.1	3.0
	Railway	1154.7	1181.2	26.5	2.3
B	Highway	504.5	510.0	5.5	1.1
	Railway	1154.7	1162.3	7.6	0.7
C	Highway	504.5	506.7	2.2	0.4
	Railway	1154.7	1155.3	0.6	0.1
D	Highway	504.5	513.4	8.9	1.8
	Railway	1154.7	1165.9	11.2	1.0
E	Highway	504.5	529.9	25.4	5.0
	Railway	1154.7	1194.6	39.9	3.5

Table 6
Increase in value of shipments by mode for the five scenarios

Scenario	Commodity flow	Without event (billions of dollars)	With event	Change	Relative change (%)
A	Interregional	2,863.8	2,856.6	−7.2	−0.3
	Intraregional	1,061.2	1,068.4	7.2	0.7
	Highway	3,064.9	3,061.8	−3.1	−0.1
	Railway	860.0	863.2	3.1	0.4
B	Interregional	2,863.8	2,858.0	−5.8	−0.2
	Intraregional	1,061.2	1,067.0	5.8	0.5
	Highway	3,065.0	3,063.1	−1.8	−0.1
	Railway	860.0	861.8	1.8	0.2
C	Interregional	2,863.8	2,852.4	−11.4	−0.4
	Intraregional	1,061.2	1,072.6	11.4	1.1
	Highway	3,064.9	3,055.9	−9.0	−0.3
	Railway	860.0	869.0	9.0	1.0
D	Interregional	2,863.8	2,846.5	−17.4	−0.6
	Intraregional	1,061.2	1,078.5	17.4	1.6
	Highway	3,065.0	3,054.4	−10.6	−0.3
	Railway	860.0	870.6	10.6	1.2
E	Interregional	2,863.8	2,839.1	−24.7	−0.9
	Intraregional	1,061.2	1,085.9	24.7	2.3
	Highway	3,065.0	3,051.3	−13.7	−0.4
	Railway	860.0	873.7	13.7	1.6

costs of highway due to the disruption of the highway network. In addition, the total commodity flows by the highway mode are shifted by $3.1 billion to the railway mode for the same reason. Even though Scenario C has fewer impacts for the mean shipment length in Table 5 than Scenario A, both the interregional commodity flows ($11.4 billion) and the total commodity flows ($9.0 billion) by highway of Scenario C are shifted more than Scenario A, as shown in Table 6.

5. Conclusion and future research

An interregional commodity flow model, incorporating input–output relationships, and integrated with a transportation network model, was implemented for the US highway and railway networks to forecast flows of 11 commodity sectors. The model was solved using a partial linearization algorithm, and provided estimates of intraregional and interregional flows and link flows by mode for each sector. In the sense of the traditional sequential travel forecasting procedure, the model simultaneously forecasts generation, distribution, mode choice, and assignment in a single procedure. The estimated commodity flows for 1993 have a reasonable correspondence with observed commodity flows.

The model was applied to estimate and evaluate the impacts of transportation network disruptions caused by an hypothesized catastrophic event. The findings may be used to identify critical sections of the network and analyze post-event reconstruction strategies. That is, the information can provide a basis for making decisions on policies to mitigate possible damages from an event by reinforcing the existing critical bridges, roads and railroads, and for planning construction of new network sections to strengthen an existing network.

Finally, the economic impacts of a catastrophic event were estimated and evaluated by analyzing changes in commodity flows and their mean shipment distances based on three hypothetical scenarios and two combinations of them. For each scenario, the model estimated the commodity flows among regions, the mean shipment length, and the shift in commodity flows from highways to railways. By comparing results with and without the event, the I-94 highway section of Scenario A was identified as the most critical section among three scenarios.

Additional research is needed to perform benefit-cost analyses of rational retrofit strategies for transportation networks. Although the model implemented in this research was limited to one year, benefit-cost analysis are required for a longer time period, such as 25 years.

In the analyses conducted to date, the regional final demands were regarded as unaffected by the hypothesized event. For a more comprehensive analysis, regional final demands should not be regarded as fixed. The response of regional final demands to the events should be estimated in response to the capacity reduction of the transportation network.

Acknowledgement

This research was supported primarily by the Earthquake Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9701785.

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