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TransNIEMO: Economic Impact Analysis Using a Model of Consistent Interregional Economic and Network Equilibria

JoongKoo Cho / Peter Gordon
James E. Moore, II / Qisheng Pan
JiYoung Park / Harry W. Richardson

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Abstract

We describe a model that integrates a multi-regional input-output model of the U.S. (50 states and the District of Columbia) with the national highway network. Interstate commodity shipments are placed on a congestible highway network. Simulations of major choke-point disruptions redirect traffic which increases the costs of some shipments. Increased costs show up in higher prices which help to determine a new input-output equilibrium. We find economic and network equilibria that are consistent. The simulations show only moderate economic impacts. We ascribe this to the resilience of highway network. The model provides state-level detail on who bears the costs of the disruptions.

JEL-Code: R110, R120, R130, R150, R400, R410, R490.

Keywords: multi-regional input-output model, highway network, interstate commodity shipments, highway infrastructure failure.

*JoongKoo Cho**
Epstein Department of Industrial and Systems Engineering
University of Southern California
USA – Los Angeles, CA 90089
joongkoc@usc.edu

Peter Gordon
Sol Price School of Public Policy
University of Southern California
USA – Los Angeles, CA 90089
pgordon@usc.edu

James E. Moore, II
Epstein Department of Industrial and Systems Engineering & Sol Price School of Public Policy
University of Southern California
USA – Los Angeles, CA 90089
jmoore@usc.edu

Qisheng Pan
Department of Urban Planning and Environmental Policy
Texas Southern University
USA – Houston, TX 77004
pan_qs@tsu.edu

JiYoung Park
Department of Urban and Regional Planning / University at Buffalo
The State University of New York
USA – Buffalo, NY 14214
jp292@buffalo.edu

Harry W. Richardson
Sol Price School of Public Policy
University of Southern California
USA – Los Angeles, CA 90089
professorhwr@gmail.com

*corresponding author

I. Introduction and Research Challenge

Economic impact models that are spatially disaggregated are part of the legacy of regional science. Aggregation to the national level obscures important details and is potentially misleading whenever positive impacts in one place cancel negative impacts in another (the "wash" effect). Aggregated results are of limited interest to policymakers because of most politicians' keen and logical interest in impacts on their local constituencies.

Inter-regional and multi-regional input-output models were first developed largely at a theoretical level over a half-century ago to address these problems (e.g. Leontief (1936, 1941), Isard (1951), Miernyk (1965) and later Polenske (1980), Miller and Blair (1985)). In recent years, there have been important advances in the regionalization of national input-output data. Yet while the available multi-regional models measure trade between regions (Hewings et al., 2002), the infrastructure over which trade occurs on the national transportation networks remains neglected. In this paper, we present applications of TransNIEMO to address this omission.[1] We add the nation's highway network to the National Interstate Economic Model (NIEMO), a multi-regional input-output model that includes the 50 states and the District of Columbia as well as 47 industrial sectors, a model we had previously developed.[2] TransNIEMO adds the nation's highway network which accommodates most of the intra- and inter-industry trade that NIEMO estimates. The new model seeks highway network and economic equilibria that are consistent with each other.

The U.S. economy is vulnerable to disruptions, including terrorist attacks and natural disasters. Modeling how disruptions at major choke points on the nation's highways might impact the U.S. economy on a state-by-state and industry-by-industry basis is of particular interest. We believe that TransNIEMO is the only operational model that can be used for this type of analysis. While this paper reports the results of hypothetical impacts on three major

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[1] Several integrated models of freight transportation and economic effects have been developed for European countries. European examples include Tavasszy et al (1998)'s the Strategic Model for Integrated Logistics and Evaluations (SMILE) for the Netherlands, Cascetta et al.(2008) freight demand simulation model applied a multi regional input-out model for Italy, and Geerts and Jourguin (2001) developed a long-term planning model of freight transportation and multimodal networks for Belgium.

[2] On a smaller scale, we have used an initial version of TransNIEMO for a three-state area to estimate more local effects economic impact stemming from a hypothetical highway bridge disruption connecting California and Arizona (Park et al., 2011).

choke points, disruptions from natural or man-made events on any other vulnerable highway link can easily be modeled by applying TransNIEMO.

In what follows, we cite the relevant literature (Section II), describe how a computable highway network and its constituent parts were assembled (Section III), explain the scenarios that were tested (Section IV), describe network flow results and economic consequences of various simulated disruptions (Section V), and wrap up with conclusions and reflections (Section VI).

II. Integrating Highway Networks with Input-Output Models

There are two standard models of the classic economic input-output (I-O) approach. The first, the Leontief demand-driven IO model, follows Leontief's early contributions (1936, 1941) with respect to how to generalize interdependencies between industries in an economy. The second, the Ghoshian supply-driven I-O model, was introduced by Ghosh in 1958 and suggested an alternative way to understand the interrelations between industries. Inter-industry linkages in the demand-driven I-O model account for technical relationships in the economy via production functions. In contrast, the supply-driven model is less transparent, suggesting fixed sales patterns, perhaps because of monopolistic markets or a centralized, planned market in which all resources are scarce except for one, and considers the best use of this non-scarce input in combination with scarce resources. This best use may be derived from a standard social welfare function (Ghosh, 1964). These are strong assumptions, but like fixed production coefficients in the Leontief model, may be plausible in the short run (Park, 2008; 2011; 2013).

Spatial extensions of the classic I-O model include interregional or multiregional I-O (IRIO or MRIO) models (Isard, 1951; Chenery, 1953; Moses, 1955); as well as empirical versions developed in the late 1970s (Polenske, 1980) and early 1980s (Jack Faucett Associates, 1983). Recently, Park et al. (2007) constructed a new demand-driven MRIO model, the National Interstate Economic Model (NIEMO), used in this paper. As demonstrated by Dietzenbacher (1997), the supply-driven I-O model can provide a more convenient formulation for estimating absolute cost increases than the Leontief price I-O model. We applied the supply-driven NIEMO in the cost estimations in this study. Our approach had been previously elaborated and empirically tested by Park (2008) and Park et al. (2008).

Turning to models of highway networks, Hillestad et al. (2009) noted that an important element of an adaptable and resilient freight transportation system includes identification and analysis of key vulnerabilities in the freight system, and simulations of possible responses to the disruption. Also, Okuyama et al. (1999) and Kim et al. (2002) applied a Midwest regional economic model and missed capturing the full set of spillover effects. Unless a model accounts for secondary effects or substitutions in the economy at the national level, policy makers will not have the full picture.

This research was elaborated to extend the geographically limited version of TransNIEMO by Park et al. (2011) to address the regional freight transportation models discussed in Gordon and Pan (2001), Pan (2006), and Giuliano et al. (2007), to analyze interregional and interstate freight flows, and to simulate the response of highway freight flows to disruptions in the national level. It uses data from the U.S. DOT's Freight Analysis Framework (FAF2) to establish a baseline of freight flows on the national highway network. It also creates highway bridge and tunnel disruption scenarios in specified regions to estimate state-level costs of highway infrastructure failure, measured in terms of increased time and distance.

III. Methods

III.1 Identifying Network Links and Centroids

The first steps in the development of TransNIEMO involved the representation of a computable version of the nation's highway network. This task involved three challenges: to identify major economic *and* network centroids; to describe and connect the important highway links; and to include the tunnels and bridges that might be choke points if disrupted. Centroid identification was the most complex of these tasks, and is fully described in Park et al. (2009).

At the metropolitan scale, defining centroids to represent sources of aggregate demand in a relatively small traffic analysis zone and connecting this demand to physical facilities at the boundary of the zone is a relatively straightforward exercise. At the national level, the same step is more challenging. Analysis zones need to define a much larger region. An economic centroid characterizing this region aggregates a much larger volume of demand than in a metropolitan level model.

Two definitions of centroid were used. The major metropolitan areas were designated as the *economic* centroids, while a representative sample of nearby highway nodal points were designated as *network* centroids. The economic centroids are defined to represent an economic center of gravity for the region, and as a result are most often near metropolitan areas that include considerable infrastructure. The transportation demand at each of the economic centroids is connected via virtual (dimensionless, costless) links to many network centroids in the vicinity of the economic centroid because it is unrealistic to load trucks onto the regional highway network connecting major metropolitan areas via a single network node at each location. We use econometric and spatial analysis to identify multiple network nodes at many highway interchanges via which to connect each regional economic centroid to the highway network. The total number of network centroids in our system is 1,877. The total number of arcs in the original FAF network is 170,773.

The Freight Analysis Framework (FAF2) highway provides link and node geographic reference data for the base network. The FAF origin-destination database employs 114 domestic regions defined in the 2002 Commodity Flow Survey (CFS) plus 17 international gateways and seven international regions. Because the goal of this study was to examine commodity or truck flows on the national highway network, we used the 114 domestic origin and destination regions in the FAF network to represent the economic centroids. There are 12,204 OD pairs representing total flows between economic centroids.

III.2 Estimating the Impacts of Highway Infrastructure Failures

The analytical framework for estimating the impacts of highway infrastructure failures on freight flows includes three steps: establishing the network baseline by loading freight flows onto the national highway system, designing scenarios for highway bridge failures and tunnel closures, and examining the changes of freight flows before and after the highway bridge or tunnel failures.

In the applications of our model, more than 275,000 highway network links were examined. The network link attributes also include capacity and speed. Link capacities were obtained from the FAF 2002 data set, which estimates capacities using the methodology in the

Highway Capacity Manual (HCM) 2000. Free flow link speeds were estimated based on link classification. An equilibrium model is applied to estimate freight flows in the baseline and for the bridge collapse scenario. Freight tonnage was converted to passenger-car equivalent (PCE) values based on the ton-per-PCE ratios estimated by Giuliano et al. (2007).

III. 3 Economic Impacts of Disruptions: NIEMO and TransNIEMO

TransNIEMO involves three sub-models, a national highway network model, a transportation cost impact model, and NIEMO (our demand-driven multi-regional input-output model). The various modeling steps are summarized in Figure 1. In that Figure, the various data sources (Data Inventory in upper-left large box) were described. The box on the left (Network Definition) was described in Section III.1; Network Disruption Scenarios (center box) were described in Section IV. Below that, Network Modeling was described in Section III.2. The upper right box (Transportation Cost Impact Model) and the box at the bottom of the Figure (Demand-Driven NIEMO) are described below this Section.

The tests described here are for a one-year disruption of selected highway links. NIEMO is linear, making it a simple matter to scale down the results to shorter periods. Three major research steps associated with the three sub-models are discussed in this section.

III.3.1 Highway Network Model

Freight analysis framework (FAF2) 2002 data were used to assemble and construct highway network links. The network was used to define bridge and tunnel collapse scenarios, and was also employed in the freight network model to estimate the changes in freight flows under various shut-down scenarios.

The highway network model is applied by combining the highway networks with the bridge or tunnel disruption scenarios. A user equilibrium (UE) model is applied twice for each test: first to develop a baseline and second by applying the scenario. The user equilibrium approach is appropriate when there is significant congestion on the network. As we are dealing with freight flows on highway networks among metropolitan regions, applying the UE algorithm is reasonable. A static user equilibrium framework is an approximation in this context, but it is computable and ensures that shortest paths are not overloaded because it respects the economic incentives faced by shippers. The results from applying the UE algorithm include the times and the distances from origin regions to destination regions. We assume that trip durations are related to truckers' labor costs and distance is associated with the other variable costs besides labor. The results from the network model simulations are used as inputs into the transportation cost impact model.

III.3.2 Transportation Cost Impact Model (Supply-side Input-Output Model) and NIEMO (Demand-driven Multi-regional Input-Output Model)

FAF provides a comprehensive data set but not all of the data are directly applicable to our research problem because services are also included in annual flows among NIEMO's industrial sectors. These service values must be excluded from the model. NIEMO freight flows are used as freight flow input values. However, NIEMO does not account for transportation shipment modes. Consequently truck proportions from FAF are used to apportion NIEMO-estimated trade flows to obtain truck shipments. These are then loaded onto the highway network.

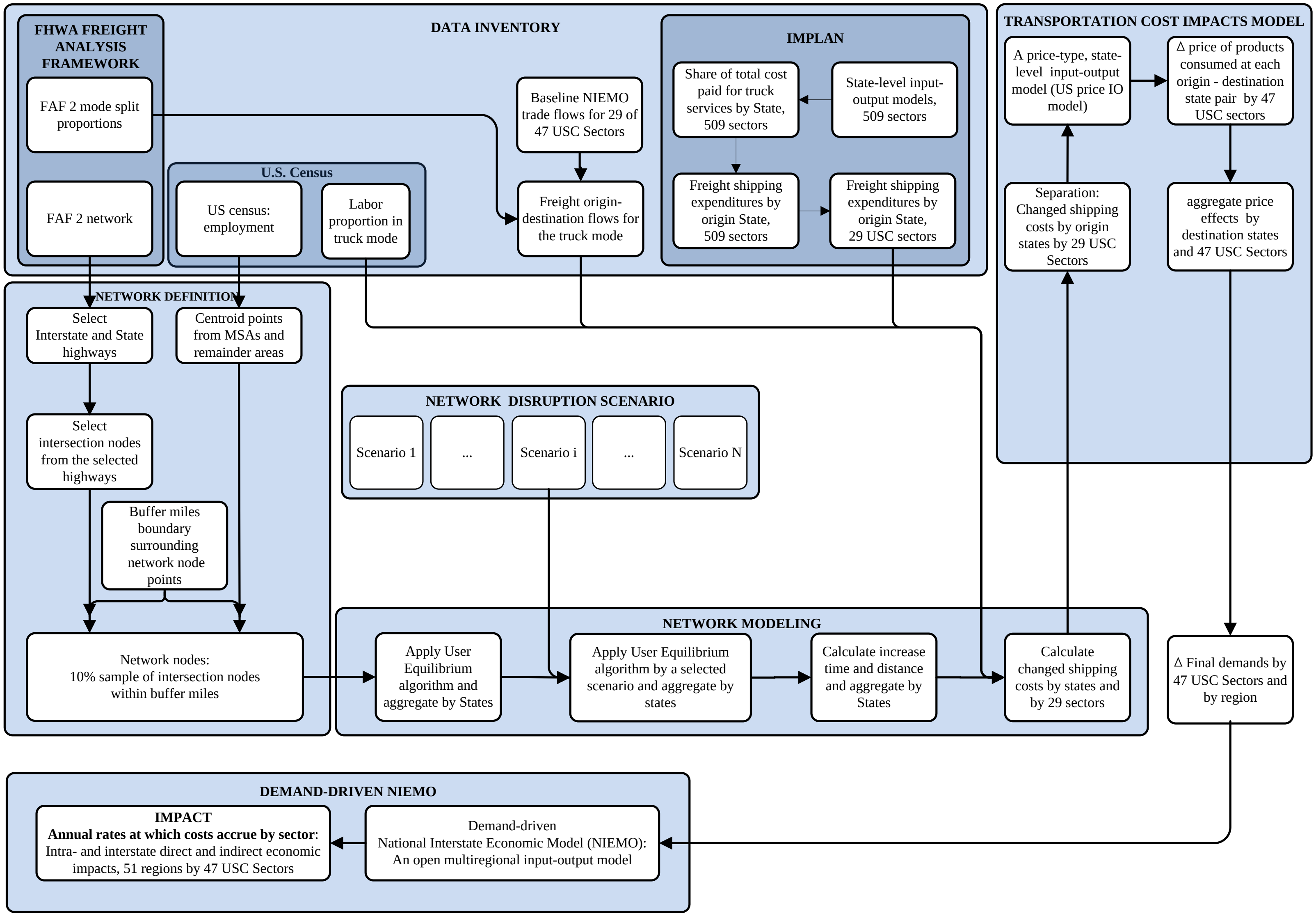

Figure 1. Framework of TransNIEMO

Increases in shipping costs will increase commodity prices. This, in turn, suppresses consumer expenditures. Consequently, we also require data on the shipping costs associated with all the flows. Total shipping costs between states are estimated using data from NIEMO, IMPLAN, and FAF as follows,

$$SC_{ij}^{k} = TTV_{ij}^{k} \times TP_{ij}^{k} \times TCV_{i}^{k} \tag{1}$$

where

SC_{ij}^{k} are aggregated shipping costs from state i to j by commodity sector k.

TTV_{ij}^{k} are total trade values obtained from NIEMO for 49 x 49 states (Hawaii is omitted).

TP_{ij}^{k} are truck proportions of total trade calculated by applying truck output values divided by total output values obtained from FAF data. Data for 114 MSAs by 114 MSAs are aggregated to 49 states by 49 states.

$TCV_{i}^{k} = \dfrac{PTS_{i}^{k}}{TIV_{i}^{k}}$ are truck costs per value. These are the truck cost proportions in origin states obtained from IMPLAN. IMPLAN's sectors are aggregated to 29 Commodity Sectors (The "USC Sectors" that we developed are described in Table A4 of larger report at website noted below). PTS_{i}^{k} are the total value of purchased services by the trucking sector and TIV_{i}^{k} are total output of industry sectors.

Increased travel time and distance proportions are estimated by applying the user equilibrium network model. Time changes and distance changes are separately modeled in equations (2) and (3).

$$T_{ij}^{k} = SC_{ij}^{k} \times \left(PTC_{ij} \times PLC\right) \tag{2}$$

where

T_{ij}^{k} are increased costs caused by the increased time of travel.

PTC_{ij} are the proportions of time changes calculated as total increased time divided by total baseline time. Data for 114 MSA by 114 MSA flows are aggregated to 49 states by 49 states.

PLC is the proportion of labor costs in operation of the transportation industry (0.65).

$$D_{ij}^{k} = SC_{ij}^{k} \times \left(PDC_{ij} \times PVC\right) \tag{3}$$

where

D_{ij}^{k} are increased costs associated with increased shipping distance.

PDC_{ij} are proportions of distance change calculated as total increased distance divided by total baseline distance. Data for 114 MSA by 114 MSA are aggregated to 49 states by 49 states.

PVC is the assumed proportion of variable costs in operation of the transportation industry (0.35).

Total increased shipping costs are estimated by adding the two increased costs, time and distance. See Equation (4).

$$\Delta SC_{ij}^{k} = D_{ij}^{k} + T_{ij}^{k} \tag{4}$$

where

ΔSC_{ij}^{k} are increased shipping costs from origin state i to destination state j for industry sector k resulting from an event. In the short run, shipping costs are assumed to be non-decreasing. In the event of an emergency, sellers can pass on higher costs in the short term. They may also cut prices because of competitive pressures, but only in the longer run.

As noted above, these increased shipping costs, ΔSC_{ij}^{k}, are passed forward and lead to increased prices at destinations, resulting in lower consumer expenditures. This approach hinges on the idea that in the short run supply chains are more fixed than the household sector's expenditure budget. Households can be expected to hold much smaller inventories than intermediate industries and are, therefore, the most vulnerable to price hikes. The most vulnerable are the ones who are impacted.

The price increases can be calculated, and then the corresponding reductions in consumer expenditures treated as reduced final demand, subject to the standard restrictions on substitutions associated with the I-O perspective. We applied the supply-driven I-O model to develop more meaningful estimates of price increases which are suggested in *absolute* costs in the supply-side application. An application of a supply-driven I-O model is summarized in equation (5).

$$\Delta P_j^k = \sum_{i=1}^{51} \left(\Delta SC_{ij}^k \times G_j \right) \tag{5}$$

where

ΔP_j^k are decreased consumer expenditures at destination j and industry sector *k*.

$G_j = (I - B_j)^{-1}$ is a 47 x 47 supply-driven input-output inverse matrix where B_j is the direct output-based technical coefficients matrix of destination state *j*.

ΔP_j^k can be aggregated either by states or by sector. $\sum_{k=1}^{47} \Delta P_j^k$ are direct impacts by states when ΔP_j^k are aggregated by sector and $\sum_{j=1}^{51} \Delta P_j^k$ are direct impacts by sector when ΔP_j^k are aggregated by state.

The reduced consumer expenditures associated with increased shipping costs drive reductions in household final demand. We assume that there are no substitution effects in the short term, and final demand is directly affected by the reduced consumer expenditures. Equation (6) applies the demand-driven NIEMO to estimate the state-by-state economic impacts resulting from these reductions in household final demand.

$$\Delta X_j^k = \mathrm{DIVS} \times \left(-\Delta P_j^k \right) \tag{6}$$

where

ΔX_j^k are decreased final outputs in destination states j and industry sector k.

DIVS=(I-DNIEMO)$^{-1}$, where DNIEMO denotes the (47x52)^2 technical and trade coefficients in the demand-driven National Interstate Economic Model (NIEMO)

ΔX_j^k can be aggregated either by states or by sector. $\sum_{k=1}^{47} \Delta X_j^k$ are total impacts by states when ΔX_j^k are aggregated by sector and $\sum_{j=1}^{51} \Delta X_j^k$ are total impacts by sector when ΔX_j^k are aggregated by state.

We applied the equation found in Berwick and Farooq (2003) to calculate truckers' labor cost per mile as

$$LRPM + \frac{\left({}^{TD}/_{S} + WT\right) * LRPH}{TD} \tag{7}$$

where

LRPM = Labor (Wage) Rate Per Mile = .493 \$/mile

TD = Trip Distance = 100 miles,

S = Speed = 65 MPH,

WT = Wait Time = 1 hour, and

LRPH = Labor (Wage) Rate Per Hour = \$17/hour.

The equation given in the literature assumes LRPH=\$10/hour and LRPM=0.29 \$/mile. We believe the current LRPH is close to \$17. As a result, we modified the numerical terms LRPM and LRPH in equation (8), and obtained \$0.9 per mile. In the literature, other variable costs are given as \$0.48 per mile, and we estimated labor cost to 65 percent of total variable cost, or

$$0.65 = 0.9 / (0.9+0.48) \tag{12}$$

IV. Scenarios

We selected interesting scenarios by identifying the nature and dimension of losses from possible disruptions along potentially major highway choke points. Two criteria were considered for selecting critical bridges or tunnels in the Interstate Highway Program. First, there should be high volumes of truck traffic on the bridge or tunnel. Second, there should be few alternatives available for detour in cases of emergency. For these reasons, we focused on the bridges over the Mississippi River and tunnels under mountain ranges.

According to the National Bridge Inventory (NBI) database, there were 599,766 bridges in the US in December 2007 (USDOT-FHWA 2008). Based on the information gathered from a variety of sources, including the American Association of State Highway and Transportation Officials (AASHTO), Historic Bridges of the U.S., and the Federal Highway Administration (FHWA) Freight Analysis Framework, there are about 28 bridges over the Mississippi River with Annual Average Daily Traffic (AADT) counts greater than 10,000.

Three scenarios were selected for this study. Tables 1 summarize relevant information for the selected bridges and the tunnel studied. The Memphis-Arkansas Memorial Bridge and Hernando de Soto Bridge accommodated 30,000 average daily truck trips in 2002 and these two bridges are relatively far away from alternative bridges. These two bridges were selected for the first scenario. Four other bridges over the Mississippi River, selected via the same criteria, were chosen for the second scenario. A tunnel disruption scenario involves the nation’s longest tunnel, the Eisenhower Memorial Tunnel under the Rocky Mountain range; which, because of its location, also has very few alternates.

Table 1. Bridges and Tunnel Selected for the Bridge/ Tunnel Disruption Scenario and Associated Truck Traffic

Scenario	Bridge or Tunnel Name	Highways (Carries)	AADTT02
Scenario One	Memphis-Arkansas Memorial Bridge	I-55 / US-61/US-64 / US-70	19,021
	Hernando de Soto Bridge	I-40	11,660
Scenario Two	Horace Wilkinson Bridge	I-10	7,268
	I-74 Bridge / Iowa-Illinois Memorial Bridge	I-74 / US 6	5,260
	Rock Island Centennial Bridge	US 67	615
	I-280 Bridge	I-280	2,240
Scenario Three	Eisenhower Memorial Tunnel	I-70	3,571

Notes: AADTT02 is the annual average daily truck traffic in FAF 2002 data.

Scenario One: Two-bridge Closure Scenario

The Mississippi River is divided into the upper Mississippi, from its source in Minnesota south to the Ohio River, and the lower Mississippi, from the Ohio to the Mississippi’s mouth near New Orleans. In comparison to the Upper Mississippi River, the Lower Mississippi River is wider and has relatively fewer bridges. For example, there are only two bridges across the borders of Tennessee, Arkansas, and Mississippi: the Memphis-Arkansas Memorial Bridge and the Hernando de Soto Bridge as explained in Table 1. These accommodate some of the highest truck traffic flows across all the bridges over the Mississippi River.

The collapse of these two bridges would impose significant impacts on the level of service provided by the transportation networks due to limited alternatives in the immediate region for re-routing flows over the Mississippi River. Our first scenario assumes bridge failures for the Memphis-Arkansas Memorial Bridge and the Hernando de Soto Bridge. We seek to estimate all consequent re-routings of freight flows on the 275,168 links in the restricted national highway network.

Scenario Two: Four-bridge Closure Scenario

In addition, we identified four bridges with the highest Annual Average Daily Truck Traffic (AADTT). These are the Horace Wilkinson Bridge on I-10 in Louisiana, the Iowa-Illinois Memorial Bridge on I-74, Rock Island Centennial Bridge on US 67, and the Interstate Highway I-280 Bridge. The I-74, US 67, and I-280 bridges are located at the border between Iowa and Illinois. Our second scenario assumes that these four bridges over the Mississippi River collapse at about the same time due to a terrorist attack.

Scenario Three: Tunnel Closure Scenario

Located west of Denver, Colorado, on Interstate highway 70, the Eisenhower Memorial Tunnel is a two-bore tunnel, 2.7 miles in length. It is one of the highway system’s highest elevation tunnels and among the longest mountain tunnels built in the Interstate Highway Program. Table 1 shows the traffic of the Eisenhower Memorial Tunnel recorded in the FAF 2002 data set. Our third scenario assumes closure of this tunnel from either a terrorist attack or a natural disaster.

V. Model results

V.1 Network Effects

Each economic centroid is connected to multiple network centroids in the vicinity of the economic centroid, and each network centroid serves as an origin for an equal share of the freight transportation requirements associated with the economic centroid. Each serves as a destination for an equal share of the demand imposed on the network at network centroids in the vicinity of other economic centroids. Once network equilibrium flows are achieved, travel times and changes in travel times between economic centroids are computed as averages across the pairs of network centroids corresponding to each pair of economic centroids. When network capacity is removed from the system, travel times on a few links decrease. These are links that are no longer accessible as a result of removing a link or links. However, alternative routes see an increase in flows and a decrease in level of service as freight flows divert away from routes that are no longer feasible.

Table 2 lists the top-20 OD pairs with the highest percentage of time difference between the baseline and four-bridge-collapse scenario, estimated from the equilibrium assignment model with capacity constraints. Based on the modeling results, the increased freight shipping time in the bridge collapse scenario was 674 million PCE*hours across all 12,204 OD pairs of economic centroids. The net increase in route travel times is 373,836 hours system-wide. Since economic centroids are associated with large, sub-state regions that are constrained by state boundaries, these results can be further aggregated to state-level results using standard GIS tools.

Similarly, Table 3 lists the top-20 OD pairs with the highest percentage of time difference between the baseline and two-bridge-collapse scenario, also calculated via the equilibrium assignment model with capacity constraints. The model estimated that freight shipping time increased 3,061 million PCE*hours across all 12,204 economic centroid OD pairs. The net increase in route travel times is considerably higher than in the case of the previous scenario, 1,573,773 hours system wide. As before, these results be aggregated to state-level values. Some numerical fidelity is lost because freight shipping times for state-to-state OD pairs are calculated from the times for corresponding economic centroids.

Table 2. Top-20 OD Pairs with Highest % Time Difference between Baseline and Four-Bridge Collapse Scenario Measured by User Equilibrium Assignment with Capacity Constraints

Origin	Destination	#Path	OD val (KPCE)	Original Network		Impacted Network		Difference		% Difference	
				Avg Time (Hours)	Avg Distance (Miles)	Avg Time (Hours)	Avg Distance (Miles)	ΔTime (Hours)	ΔDistance (Miles)	Time	Distance
Washington	Washington	25	2412.65	0.0774	2.5718	0.0832	2.5718	0.0058	0.0000	7.49%	0.00%
East St. Louis	Kansas City	143	3741.14	9.3160	265.1774	9.9774	306.6700	0.6614	41.4926	7.10%	15.65%
East St. Louis	Kansas City	117	2507.16	9.5857	283.3957	10.2616	310.0446	0.6759	26.6489	7.05%	9.40%
St. Louis	Kansas City	99	4212.47	9.0395	268.3507	9.6479	288.2723	0.6084	19.9216	6.73%	7.42%
St. Louis	Kansas City	121	5576.23	8.7973	253.8011	9.3875	281.3807	0.5902	27.5796	6.71%	10.87%
Remainder of New Jersey	Virginia Beach	65	5175.00	9.7019	262.4011	10.2464	295.6473	0.5445	33.2462	5.61%	12.67%
Louisville	Cincinnati	169	6029.04	4.0133	126.4906	4.2239	126.6708	0.2106	0.1802	5.25%	0.14%
Washington	Silver Spring	65	3591.79	0.5582	20.8432	0.5848	21.2479	0.0266	0.4047	4.77%	1.94%
Washington	Richmond	65	2197.48	4.4437	124.0159	4.6536	124.9630	0.2099	0.9471	4.72%	0.76%
Delaware	Virginia Beach	169	5030.60	8.5889	257.2477	8.9713	277.8631	0.3824	20.6154	4.45%	8.01%
Louisville	Dayton	143	4877.08	4.9912	171.2554	5.2044	172.5271	0.2132	1.2717	4.27%	0.74%
East St. Louis	Remainder of Missouri	208	4791.78	6.4026	199.8073	6.6576	211.3535	0.2550	11.5462	3.98%	5.78%
East Chicago	Chicago	231	7831.15	3.2123	72.2430	3.3392	73.6664	0.1269	1.4234	3.95%	1.97%
Baltimore	Columbus	169	1679.37	15.5931	445.8562	16.2044	436.8825	0.6113	-8.9737	3.92%	-2.01%
East St. Louis	Denver	169	608.71	24.5111	870.7580	25.4584	904.0775	0.9473	33.3195	3.86%	3.83%
Louisville	Kansas City	143	1425.34	17.4836	544.6757	18.1573	609.5848	0.6737	64.9091	3.85%	11.92%
Delaware	Richmond	169	4857.46	8.0157	235.1792	8.3229	243.4783	0.3072	8.2991	3.83%	3.53%
Louisville	Kansas City	117	776.48	17.7187	563.3867	18.3969	620.0807	0.6782	56.6940	3.83%	10.06%
St. Louis	Denver	143	1358.99	23.9899	859.9821	24.8828	881.3679	0.8929	21.3858	3.72%	2.49%
Remainder of New Jersey	Raleigh	65	381.47	13.4500	421.0213	13.9480	436.9897	0.4980	15.9684	3.70%	3.79%

Table 3. Top-20 OD Pairs with Highest %Time Difference in the Two Bridge Scenario in the FAF Network Measured by Authors' User Equilibrium Assignment with Capacity Constraints

Origin	Destination	#Path	OD val (KPCE)	Original Network		Impacted Network		Difference		% Difference	
				Avg Time (Hours)	Avg Distance (Miles)	Avg Time (Hours)	Avg Distance (Miles)	ΔTime (Hours)	ΔDistance (Miles)	Time	Distance
Memphis	Arkansas	216	4,942.52	6.077	200.0925	8.8559	232.1458	2.7789	32.0533	45.73%	16.02%
Arkansas	Memphis	216	2,898.35	5.4773	197.1962	7.601	229.9408	2.1237	32.7446	38.77%	16.61%
Memphis	Remainder of Missouri	144	3,380.14	9.2256	337.2369	11.9935	364.4715	2.7679	27.2346	30.00%	8.08%
Remainder of Missouri	Memphis	144	2,629.59	8.76	339.8415	11.0556	378.9636	2.2956	39.1221	26.21%	11.51%
Memphis	St. Louis	99	2,736.74	6.7725	287.6912	8.4565	287.8123	1.684	0.1211	24.87%	0.04%
Memphis	Tulsa	81	855.79	12.3741	447.5175	15.4327	491.103	3.0586	43.5855	24.72%	9.74%
Memphis	East St. Louis	117	1,131.81	7.1028	294.6997	8.6806	312.5435	1.5778	17.8438	22.21%	6.05%
Memphis	Oklahoma City	81	1,144.63	13.9647	492.7952	16.9553	549.5469	2.9906	56.7517	21.42%	11.52%
Tulsa	Memphis	81	859.58	11.5858	440.5571	13.958	495.1701	2.3722	54.613	20.48%	12.40%
Memphis	Kansas City	99	701.54	13.7844	507.1309	16.5921	548.2106	2.8077	41.0797	20.37%	8.10%
Mississippi	St. Louis	264	1,215.35	10.4096	486.1331	12.5198	496.123	2.1102	9.9899	20.27%	2.05%
Memphis	Kansas City	81	790.95	13.8688	512.8989	16.6625	552.8285	2.7937	39.9296	20.14%	7.79%
Memphis	Lawton	117	923.72	14.5516	539.5989	17.3091	579.7381	2.7575	40.1392	18.95%	7.44%
Memphis	Remainder of Kansas	432	791.84	15.7737	597.221	18.7524	648.3663	2.9787	51.1453	18.88%	8.56%
Mississippi	East St. Louis	312	622.94	10.7345	492.7173	12.6682	519.0557	1.9337	26.3384	18.01%	5.35%
Mississippi	Arkansas	576	2,298.91	7.173	267.8714	8.4606	275.7856	1.2876	7.9142	17.95%	2.95%
Kansas City	Memphis	81	740.43	13.1589	527.6307	15.5112	548.2904	2.3523	20.6597	17.88%	3.92%
New Orleans	St. Louis	121	348.62	13.35	665.6185	15.7326	676.0811	2.3826	10.4626	17.85%	1.57%
Kansas City	Memphis	99	640.86	13.0884	520.1453	15.4227	538.6018	2.3343	18.4565	17.83%	3.55%
Oklahoma City	Memphis	81	614.02	12.9968	485.3012	15.3035	542.0572	2.3067	56.756	17.75%	11.70%

Table 4 reports the top-20 OD pairs with the highest percentage of time difference between the tunnel baseline and closure scenarios. Based on the model calculations, the total increase in freight shipping time in the tunnel closure scenario was 576 million PCE*hours for the flows between the economic centroid OD pairs. Total route travel time increases between centroid pairs was 293,252 hours. It is clear that the bridge collapse scenario is more costly than the tunnel closure scenario in terms of total shipping costs in PCE*hours. Further, the two-bridge-collapse scenario has significantly greater freight transportation impacts on the national highway network than did the alternative scenarios. This is undoubtedly the result of the limited number of alternative routes across the lower Mississippi, and the considerable diversion of flows produced from the loss of these links. The aggregate impact on route travel times is reduced as a result of the reduced freight transportation demands the loss of these bridges delivers to many links in the network.

VI. Table 4. Top-20 OD Pairs with Highest %Time Difference in the Tunnel Scenario in the FAF Network Measured by Authors' User Equilibrium Assignment with Capacity Constraints

#Path	Destination	#Path	OD Val (KCPE)	Original Network		Impacted Network		Difference		% Difference	
				Avg Time (Hours)	Avg Distance (Miles)	Avg Time (Hours)	Avg Distance (Miles)	ΔTime (Hours)	ΔDistance (Miles)	Time	Distance
Denver	Colorado Springs	286	5,250.24	4.4701	147.2388	4.8573	163.2640	0.3872	16.0252	8.66%	10.88%
Colorado Springs	Denver	286	6,978.55	3.9356	148.9149	4.2747	154.4561	0.3391	5.5412	8.62%	3.72%
Virginia Beach	Washington	65	1,820.90	5.2506	185.4439	5.6120	194.1242	0.3614	8.6803	6.88%	4.68%
Remainder of Arizona	Tucson	48	547.62	8.1142	283.2915	8.6025	319.9456	0.4883	36.6541	6.02%	12.94%
Detroit	Cleveland	247	3,250.51	8.1479	212.1253	8.6044	201.3256	0.4565	-10.7997	5.60%	-5.09%

Colorado Springs	Colorado Springs	484	18,991.65	5.6769	195.7112	5.9879	200.9215	0.3110	5.2103	5.48%	2.66%
Richmond	Washington	65	1,966.75	4.4716	124.8251	4.7018	122.7343	0.2302	-2.0908	5.15%	-1.67%
Virginia Beach	Arlington	169	3,910.82	5.1743	186.3768	5.4103	191.9705	0.2360	5.5937	4.56%	3.00%
Washington	Washington	25	1,169.30	0.0774	2.5718	0.0809	2.5718	0.0035	0.0000	4.52%	0.00%
Phoenix	Denver	65	203.89	23.3198	894.1576	24.3305	898.9331	1.0107	4.7755	4.33%	0.53%
Detroit	Pittsburgh	221	2,536.94	11.4584	327.9988	11.9395	329.6250	0.4811	1.6262	4.20%	0.50%
St. Louis	Indianapolis city (balance)	121	1,936.33	7.9232	266.7490	8.2536	294.8386	0.3304	28.0896	4.17%	10.53%
Louisville	Cincinnati	169	2,387.55	4.0133	126.4906	4.1779	135.1950	0.1646	8.7044	4.10%	6.88%
East St. Louis	Indianapolis city (balance)	143	1,364.92	7.2922	239.3810	7.5903	263.7704	0.2981	24.3894	4.09%	10.19%
Delaware	Camden	143	2,285.84	1.3459	53.4612	1.4006	53.3452	0.0547	-0.1160	4.06%	-0.22%
New Mexico	Denver	286	1,510.40	10.0302	432.7385	10.4286	451.6375	0.3984	18.8990	3.97%	4.37%
Oklahoma City	New Mexico	198	799.78	19.2989	632.3813	20.0600	659.2125	0.7611	26.8312	3.94%	4.24%
Grand Rapids	Cleveland	171	2,194.21	10.6561	342.0840	11.0668	328.3309	0.4107	-13.7531	3.85%	-4.02%
Remainder of Michigan	Cleveland	399	2,981.19	10.2120	307.2122	10.6012	298.3683	0.3892	-8.8439	3.81%	-2.88%
Minneapolis	Wyoming	208	648.18	19.9055	777.6148	20.6623	803.8577	0.7568	26.2429	3.80%	3.37%

VI.1 Economic Consequences

We find that, as a proportion of the nation's total output, the losses experienced in all three scenarios are relatively small. We ascribe this result to the high levels of resilience (mainly redundancies) of the highway network. However, our results show that there are significant differences in state-by-state as well as industry-by-industry impacts

Tables 5A, 6A, and 7A show the estimated economic losses aggregated for States; Tables 5B, 6B, and 7B show the economic losses aggregated for sectors. Only the most impacted states and sectors are shown here; more detailed results are shown in a more detailed report which also includes more maps of highway approaches near the impacted areas are available at http://create.usc.edu/TRANSNIEMO_Dec%2031_2010_Project%20Report.pdf

As shown in Table 5A, Missouri (MO), Ohio (OH), and California (CA) are the three most impacted States in the two-bridge disruption scenario. Missouri and Ohio are near the Mississippi River and California's ports handle most of the nation's trans-Pacific trade. In terms of sectors, USC Sectors 1 (live animals, live fish, meat, seafood, etc.), 5 (other prepared foodstuffs, fats, oils), 31 (construction), and 32 (wholesale trade) are most heavily impacted by this event, as shown in Table 5B. Impacts for the case of the four-bridge disruption scenario are shown in Tables 6A and 6B. Missouri (MO), Colorado (CO), and New York (NY) are the top three impacted states. The same four USC Sectors experience the most severe impacts. Tables 7A and 7B show the results for the tunnel disruption simulation. Colorado (CO), Ohio (OH), and California (CA) and the same four USC sectors are again the most impacted.

Interestingly, several states distant from the target bridges are seriously impacted. Possible reasons for these results could be explained by the network algorithm that we applied. The UE algorithm considers traffic congestion; when there is congestion in any region, truck flows are diverted to other routes. So even though the state is not proximate to the closed bridges, that state can be affected. Second, freight volumes in the state may explain the phenomenon. For example, California is severely affected in all three scenarios although it is not near the various target bridges or the tunnel. California's two major ports of Los Angeles and Long Beach handle about 60 percent of container imports to the U.S. Large portions of these imported cargos are delivered by truck to the rest of the U.S. Third, network connections may be another factor explaining the results. If major highways are connected to the disrupted bridges and, and if a state uses that highway for significant freight movements, then that state can also be affected by the closure.

The unexpected result is that the total output losses are relatively small in both absolute and relative terms, despite the obvious importance of the facilities identified in these scenarios. There is apparently sufficient redundancy in the U.S. highway network that re-routings can be found that impose relatively small costs on truckers and on the economy as a whole.

Table 5A. Top 5 State Economic Losses: Two-Bridge Closure Scenario ($ Millions, 2001)

State	Direct Impact	Indirect Impact	Total Impact	% of U.S. Total	% change in Total Output	Total Output
OH	16.9	14.4	31.2	9.87%	0.0045%	696,020
MO	12.9	9.6	22.5	7.10%	0.0067%	336,920
CA	10.4	10.9	21.3	6.74%	0.0009%	2,254,933
TX	8.1	10.7	18.8	5.94%	0.0013%	1,434,570
IL	8.8	8.9	17.7	5.59%	0.0021%	851,737
US Total	155.3	161.3	316.6	100%	0.0018%	17,769,757
Rest of World	0.0	14.5	14.5			
Total	155.3	175.8	331.2			

Table 5B. Top 5 Sector Economic Losses: Two-Bridge Closure Scenario, by Sector ($ Millions, 2001)

Industry Sector	Direct Impact	Indirect Impact	Total Impact	% of U.S. Total	% change in Total Output	Total Output
USC31	18.8	1.1	19.9	6.29%	0.0020%	1,013,113
USC25	14.3	4.7	19.0	6.00%	0.0042%	447,184
USC32	2.4	14.5	16.9	5.33%	0.0019%	875,258
USC47	6.6	8.8	15.4	4.86%	0.0020%	755,883
USC5	9.3	5.0	14.3	4.50%	0.0050%	286,070
US Total	155.3	161.3	316.6	100%	0.0018%	17,769,757
Rest of World	0.0	14.5	14.5			
Total	155.3	175.8	331.2			

Table 6A. Top 5 State Economic Losses: Four-Bridge Closure Scenario ($ Millions, 2001)

State	Direct Impact	Indirect Impact	Total Impact	% of U.S. Total	% change in Total Output	Total Output
MO	9.2	6.5	15.7	11.20%	0.0047%	336,920
CA	4.1	4.8	8.9	6.35%	0.0004%	2,254,933
OH	4.2	4.3	8.5	6.05%	0.0012%	696,020
IN	4.4	4.0	8.4	5.97%	0.0022%	377,496
TX	3.3	4.6	7.9	5.60%	0.0005%	1,434,570
US Total	68.9	71.5	140.4	100%	0.0008%	17,769,757
Rest of World	0.0	6.4	6.4			
Total	68.9	77.9	146.8			

Table 6B. Top 5 Sector Economic Losses: Four-Bridge Closure Scenario by Sector ($ Millions, 2001)

Industry Sector	Direct Impact	Indirect Impact	Total Impact	% of U.S. Total	% change in Total Output	Total Output
USC31	8.8	0.5	9.3	6.61%	0.0009%	1,013,113
USC25	6.2	2.0	8.2	5.84%	0.0018%	447,184
USC32	1.0	6.4	7.4	5.29%	0.0008%	875,258
USC5	4.6	2.5	7.0	5.01%	0.0025%	286,070
USC47	2.9	3.9	6.8	4.81%	0.0009%	755,883
US Total	68.9	71.5	140.4	100%	0.0008%	17,769,757
Rest of World	0.0	6.4	6.4			
Total	68.9	77.9	146.8			

Table 7A. Top 5 State Economic Losses: Tunnel Closure Scenario ($ Millions, 2001)

State	Direct Impact	Indirect Impact	Total Impact	% of U.S. Total	% change in Total Output	Total Output
CO	10.7	31.7	42.4	21.91%	0.0128%	330,456
OH	10.6	5.2	15.8	8.14%	0.0023%	696,020
CA	5.8	9.4	15.2	7.83%	0.0007%	2,254,933
IN	5.8	4.8	10.5	5.44%	0.0028%	377,496
NY	4.8	5.3	10.0	5.19%	0.0008%	1,300,766
US Total	73.7	119.8	193.5	100%	0.0011%	17,769,757
Rest of World	0.0	8.3	8.3			
Total	73.7	128.1	201.8			

Table 7B. Top 5 Sector Economic Losses: Tunnel Closure Scenario by Sector ($ Millions, 2001)

Industry sector	Direct Impact	Indirect Impact	Total Impact	% of U.S. Total	% change in Total Output	Total Output
USC31	10.4	6.7	17.1	4.24%	0.0017%	1,013,113
USC32	1.1	8.6	9.7	2.42%	0.0011%	875,258
USC1	3.5	5.6	9.2	2.27%	0.0053%	173,097
USC5	4.6	4.4	9.0	2.23%	0.0032%	286,070
USC47	3.3	5.1	8.4	2.08%	0.0011%	755,883
US Total	73.7	119.8	193.5	100%	0.0023%	17,769,757
Rest of World	0.0	8.3	8.3			
Total	73.7	128.1	201.8			

VII. Conclusions

This study describes a methodology for estimating the sector-by-sector and state-by-state economic impacts of hypothetical highway bridge collapse and tunnel closure scenarios. A regional freight transportation model developed in our previous studies has been extended to endogenize and analyze interregional and interstate freight flows. It is an equilibrium model with capacity constraints. The Frank-Wolfe algorithm (Frank and Wolfe, 1956) was incorporated into the model to compute user equilibrium flows on the national highway network.

Infrastructure planning in light of the terrorist threat as well as the possibility of natural disasters and degradation from wear and tear begins with an assessment of the economic value of alternative investments. One way to assess economic value is to estimate the economic losses that would result were any element of the infrastructure degraded. A modeling approach to this problem involves very extensive disaggregation. All states and many economic sectors are engaged in continuous trade at very substantial levels. Most of this trade takes place via trucks on the national highway system (including Interstate highways and major roads). Representing all of this complexity in an operational model was our primary task. In this paper we have described the steps involved in assembling the data and testing the model. We have also described three major tests of TransNIEMO to illustrate its capabilities.

One scenario hypothesized the collapse of four highway bridges in Louisiana and at the border of Iowa and Illinois. The second scenario assumed the collapse of two bridges with the highest traffic volume over the Lower Mississippi River in the Memphis area. The third scenario hypothesized the closure of the Eisenhower Memory Tunnel at Denver, Colorado. The network and economic effects of bridge collapse and tunnel closure on were examined. The simulation results showed that bridge collapse scenario is worse than the tunnel closure scenario in terms of total shipping costs in PCE*hours of travel measured at either the regional or state level. The collapse of two bridges in the Memphis area triggers the greatest increase in freight shipping costs. The results from the equilibrium model clearly show the widespread ripple effects of the bridge collapse and tunnel closure on the national highway network while the popular all-or-nothing assignment model would limit the effects to the directly impacted highways.

From a policy perspective, one unexpected result is the small adjustments needed even when high-traffic-volume bridges and tunnels are destroyed. Re-routing involves very modest increases in freight costs. In the very short run, for trucks already en route, the additional time and distance costs could be substantial. However, once the disruptions are known, the extensive redundancy in the national highway and major roads system permits long-distance trucking companies to choose alternative routes that add little, if anything, to freight costs. Therefore route redundancy is important and maintaining state is clearly beneficial.

There are some limitations in our approach, especially in the capacity constraints on freight movement. The representation of congestion cost follows a metropolitan-level perspective that relies on an assumption of steady-state flows. This is only a first order approximation for flows in a national network. Still, there is empirical evidence of freight sensitivity to congestion costs (Winston and Langer 2006), and the user equilibrium model provides much more realistic results relative to an all-or-nothing assignment approach, especially for freight re-routing on the highways closer to the collapsed bridges. Unfortunately, passenger flows have not yet been incorporated into the equilibrium model with capacity constraints because the passenger flow data are unavailable for the FAF2002-based highway network. Consequently, the results do not reflect any interactions between passenger flows and freight flows on the national highway network.

This study only considered the re-routing of freight flows on a single mode, i.e. highway network. It did not incorporate other modes, especially the rail network. In ongoing research, the rail network will be combined with the highway network to build up an integrated freight transportation network and a multi-modal freight model is being developed to estimate the change of freight flows in the bridge collapse and tunnel closure scenarios. However, we suspect that short-run mode substitution options are very limited.

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