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Adding a freight network to a national interstate input–output model: a TransNIEMO application for California

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ABSTRACT

The state of the nation's infrastructure is the subject of widespread discussion and comment because it is thought to include many deteriorating and unsafe bridges. Ever since the terrorist attacks of 9/11, there has been increasing concern over the extent to which an attack on infrastructure could result in serious economic disruption. This research develops a model to analyze the economic consequences of an attack on a major element of the highway network. We add a freight network to a national multiregional economic impact model and make freight traffic flows endogenous. The use of a sub-national interstate model recognizes that most infrastructure planning is at the state level and most political leaders' interest is local. We base our approach on the National Interstate Economic Model (NIEMO) and refer to an elaboration that we name Transportation network and the National Interstate Economic Model (TransNIEMO). The new model enables us to study the state-specific and industry-specific economic impacts of some significant changes in the nature of highway freight movements. We tested the model for selected freight movements in and out of California. The results are entirely plausible and encourage us to elaborate and test the model for hypothetical disruptions of freight traffic throughout the US.

1. Introduction

The construction of canals and railroads in the 19th century connected the central lowlands of the US with the outer world, facilitating regional specialization, trade and economic growth and establishing the US as a major supplier of agricultural production to much of the world (USDOT, FHWA, 2004). A century later, President Eisenhower saw the importance of a national interconnected highway system. Since then, the Interstate Highway System has served most of the nation's freight movements, facilitating continuing regional economic specialization and the long-term development of the US economy.

Innovations in transportation technology and expansions of transport infrastructure bring substantial changes (Muller, 2004). Goods are now moved intermodally via diverse routes. Estimating freight movements and shipping costs among regions is essential for making investment plans throughout the economy. The same holds for investments by all the public agencies that manage the highway network system. In this vein, the correlation between freight flow and network vulnerability has been a critical research topic in both economic and transportation impact analysis.

Some insightful previous studies focus on the vulnerability issue of network segments through "disruption indices" that identify the importance of certain network links by their topological location and flow capacity on them (Jenelius et al., 2006). Typically, researchers used a disruption index and the vulnerability index to demonstrate possible impacts from a hostile entity on a targeted transportation network link (Murray-Tuite and Mahmassani, 2005). With these indices, a researcher can verify and determine the critical paths and routes that present a relatively high level of system vulnerability due to significant amount of flows and that have a high importance with respect to network connectivity (Murray-Tuite and Mahmassani, 2005). Although some paths have relatively low levels of system vulnerability serving lesser flows,

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there is no doubt that there are many direct and indirect influential variables which have critical roles in analyzing the robustness of the freight flow network. For instance, the results of supply chain performance analysis given transportation disruption experiments argue for the importance of information sharing and connectivity among entities (Wilson, 2006). Further, some recent studies used indices that demonstrate the degree of overall robustness and network connectivity. The 'Network Robustness Index' (NRI) is a case in point (Scott et al. 2006).

Furthermore, researchers eliminate some nodes or origin–destination (OD) pairs from the target network to identify the correlation between nodal connectivity and flow capacity. Their results show the importance of this field of research to achieve practical results regarding economic impacts and path building methodologies (Murray et al., 2007). These interesting network disruption experiments and associated economic impact analyses motivated our research on regional economic impact analysis at the subnational level, providing not only for a nation-wide analysis disaggregated to the level of states and counties.

Improved analysis is now possible because the Federal Highway Administration (FHWA) has integrated shipments data into the Freight Analysis Framework (FAF). While the FAF data contain important capacity information, the FAF data do not include actual freight flow data on US highway networks by commodity class. Our operational multi-regional input–output model, the National Interstate Economic Model (NIEMO; Park, et al., 2007) was the source of interstate shipments by commodity and non-commodity class. Our research plan was to use both tools to find ways of allocating commodity-specific interstate trade to the national highway network. Any major flow disruption could then be diverted to second-best routes, the costs of the diversion could then be estimated and NIEMO could be used to determine a much fuller inventory of economic impacts.

Up to now, there has been something of a divorce between two important branches of spatial modeling: transportation (and often land use) and economic impact analysis. Integration between these two approaches is important because changes in economic activity have consequences for transportation while changes in the transportation network have implications for economic development.

This study is an initial trial of this focus: We study commercial goods movement and trade between metropolitan areas and its economic cost impacts for the case of a hypothetical terrorist attack on a major bridge. There would be several other costs such as additional inventory holding costs, overnight stay costs, lost sales, and rescheduling costs to be considered. However, only increased shipping costs because of rerouting are considered to estimate direct impacts in this study. We do not focus on estimating total costs and benefits in this paper, and we frequently point this out in our research. Our model works best when it focuses on business interruption impacts. To respond to a real event, we could collect other costs via surveying the relating companies and organizations. However, this study measures partial costs resulting from rerouting rather than the total impacts of an event. Even though this paper reports a California experiment, the success of our proof-of-concept application makes it possible to broaden tests and applications of TransNIEMO to the rest of the US.

While NIEMO is spatially disaggregated only to the state level, the transportation nodes for freight modes are the major metropolitan areas, which are the dominant centers of economic activity. Furthermore, in most states there is one or more major metropolitan area: The non-metropolitan regions in selected cases also account for a significant proportion of state gross domestic product and freight O–D movements. Although local governments are mostly responsible for transportation infrastructure planning within their jurisdictions, most highways serve areas beyond their boundaries.

In previous work estimating the indirect and induced effects of impacts associated with capacity losses at the twin ports of Los Angeles-Long Beach, Gordon et al. (2005) showed that two-thirds of the impacts leak outside the region. But without an interstate model such as NIEMO, we would have had no idea where these leakage effects might occur. In this paper, we describe TransNIEMO, which links the nation's highway network with the interstate model. We describe freight movements between the nation and California and the economic losses from their interruption. We plan to extend the research to achieve a parallel integration of the national and regional railway networks.

2. Niemo

NIEMO is a 47-sector-52 region input–output model that is fully operational. The idea for such a model has a long history stretching back to Isard's suggestion of the "ideal interregional model" (Isard, 1951, 1960) and Leontief's valiant but failed attempt to operationalize a variant of the model in the 1960s. A general single-region (or national) input–output (IO) model is useful for developing an understanding of economic activity within a region in terms of the region's inter-industrial relationships. Because of the simultaneous simplicity and meaningfulness provided by a system of linear, fixed relationships between industries, IO models have been widely applied to analyze short-term economic impacts. In the market economy, inter-industrial relationships play a key role in tracing production changes throughout an economy when final demand for any industry's outputs changes (Miller and Blair, 2009). However, the importance of sub-national models has long been recognized. Aggregation accounts for the loss of information, especially when positive effects in one area cancel negative impacts in another (Park and Gordon, 2005). It is also clear that most politicians have a keen interest in local constituencies. To say that NIEMO has succeeded where Leontief failed is not an immodest statement, but rather a reflection of the improvements in databases and computing capacity over the past 30 years. However, building bridges among the various data sources remained a substantial task.

NIEMO is not merely a replica of the original design as conceived by Isard and Leontief. Rather, NIEMO rests on the successful integration of state-level input–output information with data from the Commodity Flow Survey (CFS). Since 1993, the Commodity Flow Survey (CFS) has been the largest single nationwide data source for freight movement flows (USDOT, RITA and BTS, 2006). The Bureau of Transportation Statistics and the Census Bureau collect CFS data from a sample survey of industries through the Economic Census. Although the CFS provides wide range of commodity shipments and multimodal movement data with 5-year cycle updates of 1997 and 2002, some user groups have not been satisfied with its content details (USDOT, RITA and BTS, 2005). The most commonly addressed weaknesses of the CFS are its incomplete coverage by commodity sectors and regional detail, and its inability to fully capture imported goods trade (Southworth, 2005; Park et al. 2009; Giuliano, 2007). ORNL (2000) showed that the CFS estimates cover less than 75% of all the freight tons moved annually in the US, because the survey drops many establishments classified as farms, forestry, fisheries, construction, transportation, governments, foreign establishments, services, and most retail activities.

Nevertheless, Park et al. (2009) managed to estimate interstate trade flows, applying an Adjusted Flow Model and a Doubly-constrained Fratar Model. The approach depends on 1997 CFS and 2001 IMPLAN data. To reconcile different definitions and classifications of the commodities among multiple data sources, the investigators created a new commodity sector scheme, referred to as the "USC Sectors." Several applications of the initial version of NIEMO (excluding interstate service trade) show that the state-to-state trade flows and the flows between the states and the rest of world for the 29 USC commodity sectors are all readily computable (Park et al., 2008; Park, 2008; Richardson et al., 2007).

3. Freight and network flows information

Freight movements provide fundamental information on economic structure and relationships among economic and geographic entities. This means that network activity and other economic activity are integrated. They cannot be studied in isolation. Yet, this is what most analysts do. The challenge has been to assemble the necessary information to facilitate integrated modeling.

Modeling work integrating transportation and the economy has been developed in Europe since the early 1990s. For example, the Strategic Model for Integrated Logistics and Evaluations (SMILE) developed by Tavasszy et al. (1998) is one of the comprehensive models developed for the Netherlands. The model splits total freight flows on Dutch transportation systems into two types, based on whether or not the freight flows are directly related to production or consumption in the Netherlands. Another aspect of SMILE is that it integrates the decision system for warehouse location and multi-modalism into freight transportation. There are other MRIO applications combining freight transport modeling in Europe, for example, the Italian national model (Cascetta et al., 2008) and a model for Belgium (Geerts and Jourguin, 2001).[6]

We begin by trying to combine the CFS with other data sources to overcome its shortcomings. The US Department of Transportation created the Freight Analysis Framework (FAF) in 2002 to further investigations of freight activity. FAF is a comprehensive database for policy analysis (USDOT, FHWA, 2006) that provides more comprehensive information on freight flows by mode based on the same sector codes as the CFS. The framework also forecasts future freight activities. The USDOT's continuous effort to improve the FAF data set made it possible to release the latest version of FAF 2.2 in November 2006 (USDOT, FHWA, 2006). The FAF 2.2 release includes origin and destination commodity flows among 138 integrated MSAs or equivalent sub-state regions on the basis of 2002 data expressed in tons and dollar values by transportation mode and by Standard Classification of Transported Goods (SCTG) sector (USDOT, FHWA, 2006). Unfortunately, there are discrepancies between these data and other standard data sources because of the inclusion of service estimates in the data for commodity sectors.

In addition to government efforts to improve data resources, other research groups have also tried to construct better data sets. Ham et al. (2005) integrated interregional, multimodal commodity shipments and transportation network flows, formulating an alternative to the traditional four-step travel forecasting approach of trip generation, trip distribution, mode choice, and network assignment. Based on 1993 CFS data, the research was conducted for 11 commodities plus construction and service sectors. Additionally, they constructed a network consisting of 167 nodes and 532 links useful for analyzing the truck commodity flows based on the USDOT's 1997 National Transportation Atlas Database (NTAD).

Giuliano et al. (2007) estimated Los Angeles intraregional freight flows combining various sources on trade and transportation datasets. In addition to the 1997 CFS, the research reconciled IMPLAN, WISERTrade, Caltrans' Integrated Transportation Management Systems (ITMS), Transportation Analysis Zones (TAZ), Waterborne Commerce of the US (WCUS) and airport data from RAND. Although this work was limited to the highway network within one area, the results suggest the potential for expanding the approach to other metropolitan areas.

Recently, the study conducted by Ivanov and Moore (2008) estimated a similar economic impact of freight transportation on the closure of I-5 and I-90 because of flood and snow in the winter season of 2007–2008. They surveyed a total of 2758 trucking industries and freight-dependent sectors to estimate direct additional costs resulted from the highways closures. After that, they applied Washington State input–output model developed from IMPLAN for the total economic impact estimates. Their approach is relatively unusual because the direct impact estimates were obtained from a survey. We have plans to test the TransNIEMO results on closure of I-5 and I-90 highways in a future research. Such tests are always complicated because the *ceteris paribus* assumption cannot be invoked.

The availability of highway network data is important. Freight transportation is overwhelmingly an interstate activity, accounting for 73% of total ton-miles (USDOT, BTS, 2002). The data for this research are primarily via highways. However, rail, air, and water networks cannot be ignored because freight goods are often transported via multimodal transportation networks (Southworth and Peterson, 2000), and we plan to address integrating the other modes in future research.[7] The National Highway Planning Network (NHPN) has about 452,000 miles of roads, of which the Freight Analysis Framework (FAF) accounts for 245,500 miles. This includes 46,380 miles of Interstate Highways, 162,000 miles of National Highway System (NHS) roads, 35,000 miles of other national roads, and 2125 miles of urban streets and rural arterials.

4. Methodology

The application of TransNIEMO involves two major steps:

i. Estimation of increased shipping costs because of a major disruption of the constructed highway network system.
ii. State-by-state economic impact analysis applying NIEMO in light of a decline in household consumption, resulting from price increases for products shipped via second-best routes.

The application of TransNIEMO starts with the estimation of increased costs on the highway network system for a plausible scenario, e.g., destruction of a major bridge. Fig. 1 shows the framework for our research model. Step-by-step methodological explanations for estimating increased shipping costs follow. The test described here is for a 1-year disruption. The linearity of the models makes it possible to provide estimates for any study period.

We established the basic highway network dataset by obtaining the national highway network data of the Freight Analysis Framework, available via download from the Federal Highway Administration (FHWA). We pruned the small arterials and local by-ways to reduce the computational burdens, but retained sufficient redundancy to avoid sacrificing realism. Most truck drivers delivering freight minimize time costs by using higher design facilities

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[6] Also, Spatial Computable General Equilibrium (SCGE) models have been combined with freight transport modeling, for example, CGEurope moel (Bröcker, 1998; Bröcker, 2003), the Dutch SCGE model of RAEM (Elhorst and Oosterhaven, 2006),the Swedish SCGE model (Sundberg, 2009), and the Italian SCGE model (Roson, 1995).

[7] Transportation network data from the Center for Transportation Analysis (CTA) are good sources of network data to analyze multimodal routings. These are available at http://cta.ornl.gov/transnet/. The CTA networks can be applied once TransNIEMO is extended to a multimodal application.

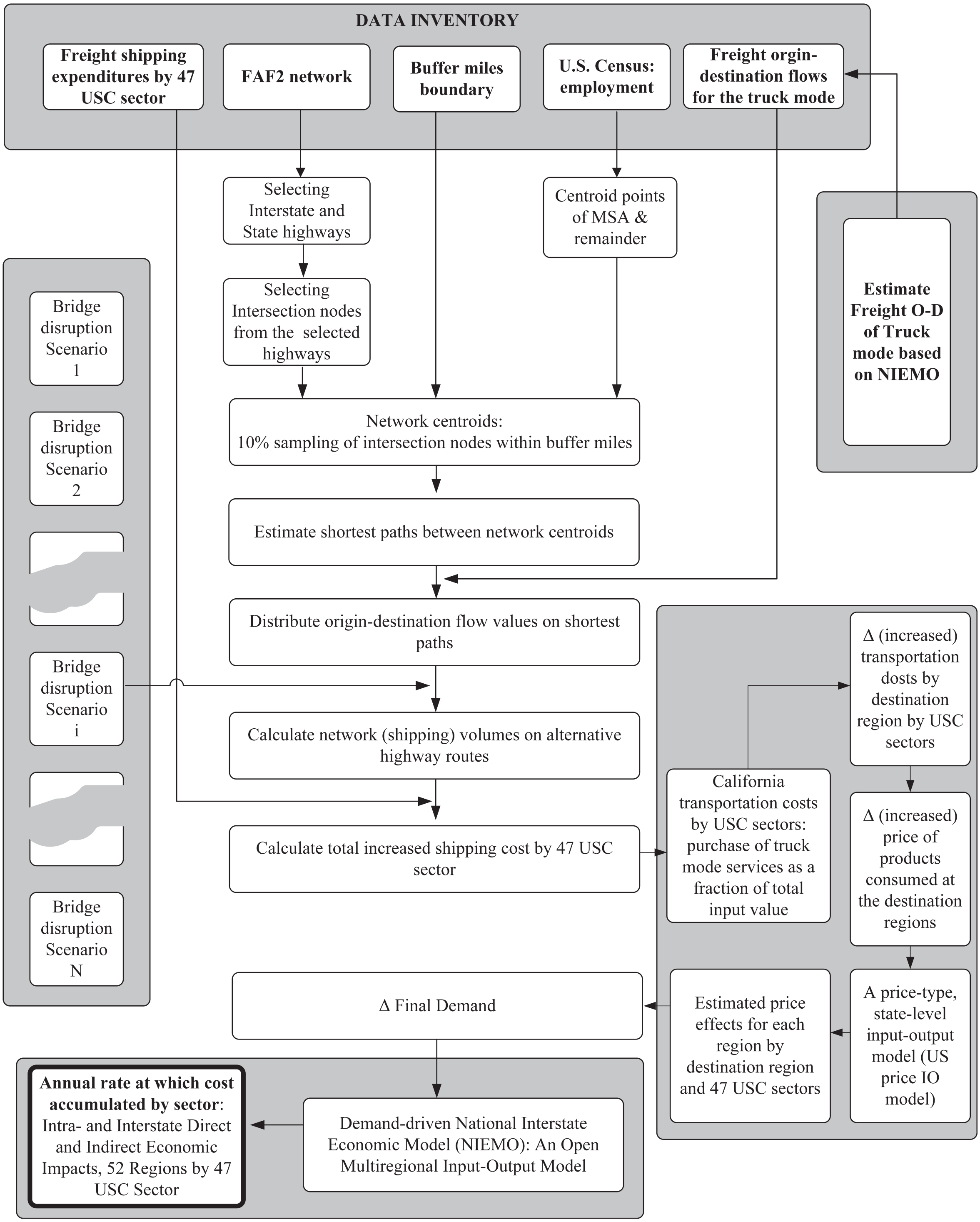

Fig. 1. TransNIEMO: data and modeling process.

such as the Interstate Highways (for example, I5, I10, I405, etc.), US Routes (for example, US101, US395, etc.), or State Routes (for example, SR-11, SR-125, etc.) to the maximum extent possible. In local areas, however, lower design facilities such as county roads and off-interstate business markers connecting interstate highways in city areas can be used to reduce costs. We used these guidelines to build a base national map for the TransNIEMO applications that includes the three major highway networks and some local roads.

Because NIEMO currently does not have multimodal information, we established the proportions in the O–D data that correspond to the trucking mode based on the FAF 2.2 data. Interstate trade information from NIEMO was multiplied by the proper proportions to determine the truck O–D requirements. This step necessarily excluded the services sector information in the FAF 2.2 O–D pairs. Although FAF 2.2 involves 138 sub-state regions, we excluded 17 FAF international gateways and 7 FAF foreign trade regions, and considered only domestic sub-state regions. Thus, our

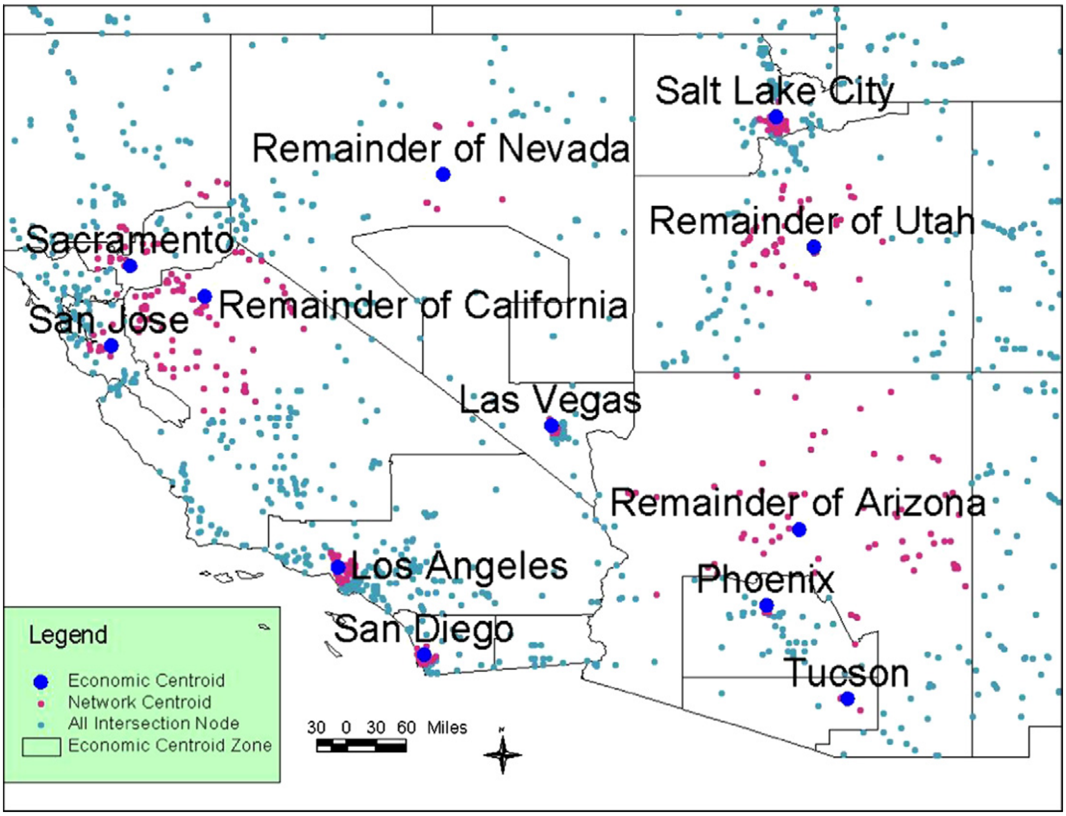

Fig. 2. Example of network centroids.

examples do not include any freight gateways (USDOT, FHWA, 2006).[8] The sub-state regions are largely equivalent to Metropolitan Statistical Areas (MSAs) and the remainder (non-MSAs) areas.

We generated *geographical centroids* corresponding to the 114 sub-state regions to combine the truck O–D data with a GIS map file. However, because the centroids do not reflect the locations of economic activities associated with each region, we adjusted the geographic centroids using city-level employment figures available from the US Census Bureau. At first, we extracted the longitude (x) and latitude (y) of geographic centroids from polygons of all cities within each MSA and the remainder of the MSA. Then we combined the extracted geographic centroids with city level employment data. Afterwards, we created a centroid for each MSA and its remainder to calculate a weighted location averaged from all city centroids using city employment data. For example, if a MSA has ten cities, ten pairs of longitude (x) and latitude (y) of geographic center points are obtained. The proportional employment of each city to total employment in the MSA is calculated and multiplied by each x–y pair. Finally, the average value of the weighted x–y coordinates are calculated and labeled as *economic centroids*. The adjusted economic centroids better represent the economic center of activities in the MSAs and various remainder areas.

One problem with representing the national economy with only 114 economically weighted centroids is that this limits the number of relevant paths between each origin and all destinations to only 114. This is somewhat unrealistic and defeats some of the objectives of the research, i.e., identifying changes in freight flows affecting alternative routes and the cost and activity changes that result. Further, applications of TransNIEMO present the risk of infeasible solutions if network disruptions are sufficient to isolate supply or demand locations.

This is not an unusual problem modeling user behavior on networks. The simplest way to predict economic behavior has been to assume perfect information and rationality on the part of economic agents. This is usually a reasonable and productive approach, and is adopted here. However, it is sometimes necessary to better account for limitations on travelers' states of information or the complexity of travelers' objectives when predicting network flows. This calls for a stochastic network equilibrium approach in which the probability of route choice varies smoothly with route and costs, rather than being represented as a binary outcome. In this case, the problem is somewhat simplified because the distances involved dictate that line-haul costs dominate congestion costs.

To account for the relevance of multiple shortest paths between sub-states regions, we developed an approach for selecting and associating nodes representing physical intersections on the highway network with O–D pairs. Estimated shortest paths will pass through one or more of these physical intersection nodes, the majority of which are in the vicinity of economic centroids associated with MSAs. These locations are used to represent the sites at which economic demand for transportation is imposed on the network. To select the intersection nodes as the starting points of truck freight shipments, we defined buffer-zone boundaries

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[8] NIEMO's interstate trade data are from the Commodity Flow Survey (CFS). Even though a good arrives in the US at an entry/exit point, CFS counted it as having an origin or destination on the US, side of the border. FAF2 was based on CFS for domestic freight movements and added other international shipments based on other sources, e.g. TransBorder Freight data from BEA. While FAF2 does account for international freight movements by mode, it is risky to combine these with domestic trade data from CFS that already include international trade information and may cause double counting problems. Thus, to be conservative and consistent with NIEMO's trade data source, we only applied the domestic trade information from FAF2, because we only applied freight coefficients from FAF2, not trade flows. It should also be mentioned that the 17 international entry/exit points in FAF2 are not located in California and Arizona.

around economic centroids, differentiated by the size of the sub-state region. If intersection nodes are located within the defined boundary, we selected and labeled them *network centroids*. These represent the greatest level of spatial detail associated with the transportation network.

To select network centroids, we defined the buffer-mile boundaries for sub-state regions. For the MSA regions, we applied 35-mile buffer boundaries. For the remainder areas, we applied several criteria: 35, 50, 75, 100, and 200 miles of buffer boundaries, depending on the geographic size of each MSA.

Each buffer radius is selected as follows:

$$M_i = \frac{\sqrt{S_i}}{2} \tag{1}$$

where M_i is buffer size, S_i is the size of each region and i is an index identifying each non-MSA area. If we assume the shape of region as a circle, $\frac{\sqrt{S_i}}{2}$ approximates the radius of the region. Based on the approximate radius, we established five different criteria as follows.

i. 35 miles if $M_i \leqslant 75.7$.
ii. 50 miles if $96.1 \leqslant M_i \leqslant 98.0$.
iii. 75 miles if $155.6 \leqslant M_i \leqslant 201.4$.
iv. 100 miles if $210.4 \leqslant M_i \leqslant 244.0$.
v. 200 miles if $257.4 \leqslant M_i$.

Even though the values of M_i for Maine and Maryland are 63.0 and 69.9 respectively, we applied 100-mile boundaries because of the narrow shape of these regions. Still, these criteria identify an intractably large number of network centroids, leading to a relatively detailed network representation that is computationally unwieldy. To reduce the computing burden, we randomly selected 10% of the network centroids associated with each economic centroid.[9] Fig. 2 shows the selected network centroids.

At the metropolitan level, it is standard practice to use an equilibrium cost flow model to predict network flows. Applying such a minimum cost flow model requires supply and demand nodes, link congestion functions, and shipping volumes among O–D pairs. The O–D volumes on the network links are determined along with the equilibrium cost link flows. In the case of the FAF O–D data, however, the standard equilibrium cost flow model is inappropriate because interurban and interstate line-haul costs dominate congestion costs. If a critical bridge located within a metropolitan area is eliminated, an equilibrium cost flow model would be appropriate. Because we assume that the critical bridge is between the border regions of the two states, applying a shortest path model would be appropriate. Finding shortest paths between O–D pairs becomes a combinatoric problem. In this research, we enumerate the number of paths between various sub-state regions by defining paths between all possible network centroid pairs involving the two regions. We distributed truck O–D volumes from economic centroids onto sampled network centroids using even weights of $1/n$, where n is number of enumerated paths linking the two regions. Even weights of $1/n$ may not be reasonable in a real world example. Our team is developing an improved method to weight the distribution of alternatives, and this will be applied in subsequent research.

The cumulative volume of freight so distributed on a highway is considerably less than the capacity of the highway links. The increased miles associated with shipping commodities before and after removing various bridges from the network are used to estimate increased trucking costs for each industry sector.

To calculate total shipping cost, we combine shipping cost per trade values, total shipping values and shipping cost per mile. We have two pieces of information: shipping cost per trade value for the truck mode and shipping distance from applications of the shortest path algorithm. Table 1 shows the example of California.

Table 1
California costs of purchasing truck mode services as a fraction of the total input value, 2001. *Source*: Raw data was obtained from 2001 IMPLAN software package “commodity balance sheet”. The authors aggregated from IMPLAN sectors to USC sectors using conversions developed by Park et al. (2007).

USC Sector	Description	PTS[a] ($M.)	TIV[b] ($M.)	TCUV[c]
USC01	Live animals and live fish and meat, fish, seafood, and their preparations	137.3	7892.6	0.0174
USC02	Cereal grains and other agricultural products except for animal Feed	328.8	21337.3	0.0154
USC03	Animal feed and products of animal origin, n.e.c.	120.9	4060.2	0.0298
USC04	Milled grain products and preparations, and bakery products	147.9	10401.8	0.0142
USC05	Other prepared foodstuffs and fats and oils	631.1	32475.7	0.0194
USC06	Alcoholic beverages	173.9	9869.6	0.0176
USC07	Tobacco products	0.1	15.0	0.0045
USC08	Nonmetallic minerals (monumental or building stone, natural sands, gravel and crushed stone, n.e.c.)	26.0	1194.7	0.0218
USC09	Metallic ores and concentrates	4.1	221.1	0.0185
USC10	Coal and petroleum products (coal and fuel oils, n.e.c.)	117.6	41272.0	0.0028
USC11	Basic chemicals	48.3	3024.6	0.0160
USC12	Pharmaceutical products	85.9	20064.7	0.0043
USC13	Fertilizers	25.3	1070.3	0.0236
USC14	Chemical products and preparations, n.e.c.	201.8	10496.8	0.0192
USC15	Plastics and rubber	459.2	15633.8	0.0294
USC16	Logs and other wood in the rough and Wood products	169.4	6675.9	0.0254
USC17	Pulp, newsprint, paper, and paperboard and Paper or paperboard articles	187.5	7193.4	0.0261
USC18	Printed products	326.8	20040.6	0.0163
USC19	Textiles, leather, and articles of textiles or leather	273.5	21400.1	0.0128
USC20	Nonmetallic mineral products	390.2	8911.2	0.0438
USC21	Base metal in primary or semifinished forms and in finished basic shapes	123.2	5403.2	0.0228
USC22	Articles of base metal	246.1	17885.7	0.0138
USC23	Machinery	220.0	25935.1	0.0085
USC24	Electronic and other electrical equipment and components, and office equipment	293.6	154741.2	0.0019
USC25	Motorized and other vehicles (including parts)	203.2	14856.5	0.0137
USC26	Transportation equipment, n.e.c.	183.0	18052.5	0.0101
USC27	Precision instruments and apparatus	91.5	27226.5	0.0034
USC28	Furniture, mattresses and mattress supports, lamps, lighting fittings, and illuminated signs	156.7	8729.6	0.0180
USC29	Miscellaneous manufactured products, scrap, mixed freight, and commodity unknown	142.4	16274.3	0.0087
Average		190.2	18357.1	0.0104

[a] Purchase of truck services ($M).
[b] Total input unit value ($M.).
[c] Truck cost per unit value.

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[9] While TransNIEMO was designed to address national level transportation network disruption, we restricted this test, to two states, and to network links involving California and Arizona. The total number network nodes for the whole US in our network file is nearly 18,700. Because of many redundant paths associated with calculating shortest paths, treating a network of this size was intractable. We selected a 10% random sample of the set of available network nodes, which still provided a highly connected and reasonably realistic representation of the national network. The final number of nodes selected is 1872 and the total number of network miles represented is approximately 394,788 miles. The California and Arizona highways constituting our experimental network accounted for approximately 20,126 network miles and 75 origin-destination pairs (54 in CA and 21 in AZ). This research focused only on domestic OD nodes to determine shortest paths and excluded external, international nodes. The trade flows applied in NIEMO already include international trade and were distributed to the domestic OD pairs.

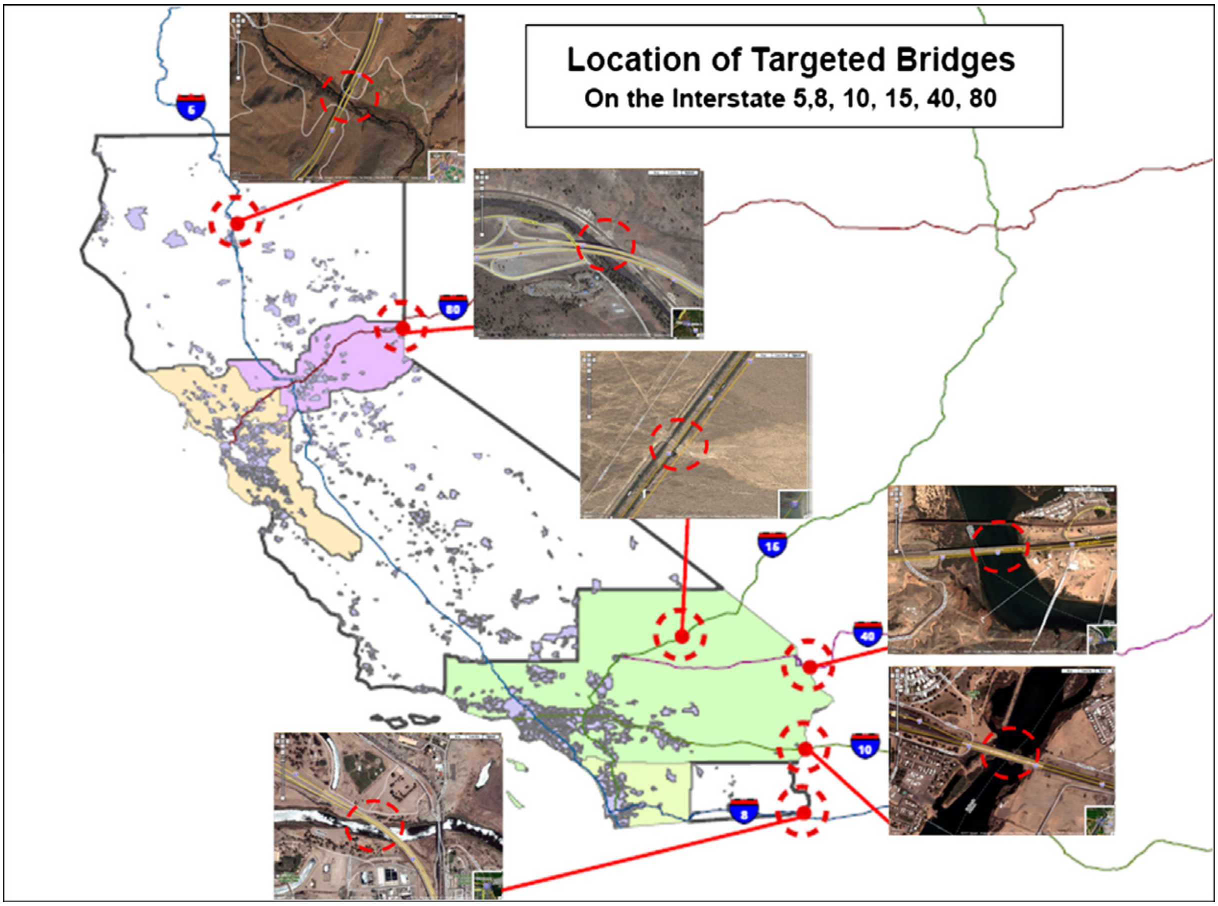

Fig. 3. Location of scenario bridges on interstate freeways.

The increased shipping cost, in turn, drives increased prices, and induces a decline in consumer expenditures. We simplify this mechanism with price and quantity of the product in the market. Assuming that total value equals the product of price and quantity, increased shipping cost raises the dollar value of products by increasing product costs. Assuming that consumers' income remains fixed, product consumption is decreased because of increased total cost. In other words, market demand is decreased. This decreased demand reduces the production of goods. The process defines how the market economy is impacted by the increased transportation costs. While we assume a very simple relationship between the concept of increased shipping cost and the associated reduction in demand in this version of TransNIEMO, we will develop discussion more elaborate representation of this mechanism in a future study.

Modeling this effect is approached as follows. With the assumption that all increased shipping costs are passed forward as any price increases, we used a supply-driven I–O model. Dietzenbacher (1997) showed that the supply-driven I–O model is to a better formulation for estimating price increases than is the Leontief price I–O model when *absolute* costs in the value-added sectors are available. As a result, these increased prices lead to reduced final demands. NIEMO is then applied to estimate the state-by-state economic impacts resulting from these reductions in final demands.

5. Highway network impact analyses

The goals of this research were to develop an appropriate database resource for adding a transportation network for NIEMO (TransNIEMO), but also to test the empirical implications of tying freight flows to physical infrastructure. In addition, our aim was to trace the transportation and output impacts in California following final demand changes induced at any location within the national economy, as well as the transportation and output impacts in each state resulting from final demand changes in California. In short, these dual objectives are (1) to better reconcile economic impact and transportation modeling, and (2) to integrate the analysis of a regional economy (in this case, California) and the national economy. Largely because of its relevance to homeland security, we selected a scenario based on eliminating access to highway bridges. We selected Arizona because it borders California.

To select a target bridge, we selected interstate highways in California by searching for bridges on the interstate highways. When we determine the candidates from among many bridges, we referred to a detailed map and selected one for which there are few alternative routes. Fig. 3 shows the selected scenario bridges. We chose a bridge on Interstate 10 from among six candidate bridges.

Fig. 4 describes the changes in alternative pathways that result from the loss of a key bridge serving I10. The disrupted I10 route is coded as Route 3. The map at the bottom of Fig. 3 shows that Route 3 is eliminated by the disruption of the key bridge. Table 2 shows changes in the number of available paths and in the dollar values of shipping on highway shortest paths. We calculated the entries in the columns labeled "# of paths" and "$ value" at the network cuts where shortest paths cross these states' borders. 'Baseline' shows results before disruption of the bridge and 'After' illustrates the results after disruption of the bridge. While the number of paths and the dollar value of shipments associated with I10 (Route 3)

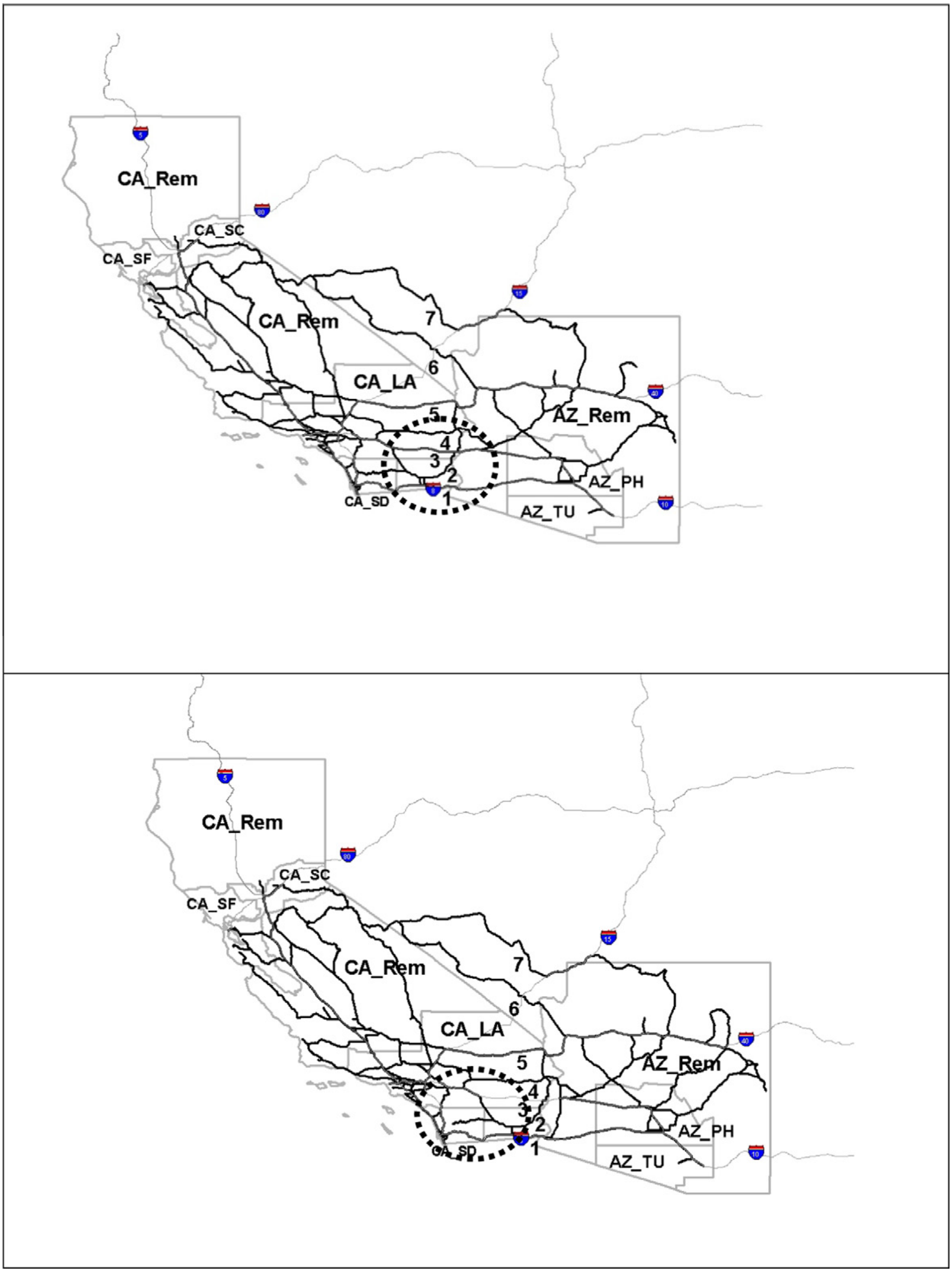

Fig. 4. Shortest paths before (upper diagram) and after (lower diagram) elimination of a key bridge on highway I15: CA to AZ.

declined dramatically, State Highway 60 (S60, Route 4) received most of this shipping volume and also accounted for increases in the number of paths in use.[10]

6. TransNIEMO results: the case of California and Arizona

If a major bridge linking California and Arizona on the I10 is eliminated, most shortest-path travel would shift to the adjacent S-62 freeway. Table 3 shows increased miles between origins and destinations based on diversions to new shortest paths. The last column "Change in Miles," shows the percentage increase in path

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[10] Since we applied a shortest-path algorithm, only traffic on the missing link was re-routed.

Table 2
Changes in the number of paths and dollar values of shipping on highways resulting from the elimination of major bridges: CA to AZ.

Route Highway	**1** I8	2 S78	3 **I10**	**4** **S62**	5 I40	6 U95	7 S375	Total
# of paths								
Baseline (*B*)	140	72	**510**	**13**	321	72	6	1134
After (*A*)	377	3	**0**	**316**	360	72	6	1134
$D = (A) - (B)$	237.0	−69	**−510**	**303**	39	0	0	0
Change (%)	169.29	−95.83	**−100**	**2330.77**	12.15	0	0	0
Dollar value								
Baseline (*B*)	186.1	176.3	**11030.1**	**8.1**	282.3	229.7	4.3	11917
After (*A*)	2492.7	1.5	**0**	**8819**	369.8	229.7	4.3	11917
$D = (A)-(B)$	2306.6	−174.9	**−11030.1**	**8811**	87.5	0	0	0
Change (%)	1239.51	−99.17	**−100**	**108,847.06**	30.98	0	0	0

Note: Unit: $ millions.

Table 3
Increases in miles traveled between economic centroids: California to Arizona.

	Origin	Destine		Number of path	Total miles of path		Change of miles	
ID	Name of region	ID	Name of region		Before (1)	After (2)	$D = (2) - (1)$	Change[a] (%)
8	CA Los Angeles	5	AZ Phoenix	65	24,528	27,441	2913	11.88
8	CA Los Angeles	6	AZ Tucson	52	25,742	26,590	848	3.29
8	CA Los Angeles	7	AZ remainder	156	77,266	79,767	2501	3.24
9	CA Sacramento	5	AZ Phoenix	20	15,467	16,053	587	3.79
9	CA Sacramento	6	AZ Tucson	16	14,256	14,562	305	2.14
9	CA Sacramento	7	AZ remainder	48	39,754	39,794	40	0.10
10	CA San Diego	5	AZ Phoenix	45	16,436	16,947	510	3.10
10	CA San Diego	6	AZ Tucson	36	15,306	15,306	0	0.00
10	CA San Diego	7	AZ remainder	108	52,006	52,876	869	1.67
11	CA San Jose	5	AZ Phoenix	45	33,168	34,713	1545	4.66
11	CA San Jose	6	AZ Tucson	36	30,771	31,458	687	2.23
11	CA San Jose	7	AZ remainder	108	86,494	86,628	134	0.16
12	CA remainder	5	AZ Phoenix	95	57,824	60,205	2381	4.12
12	CA remainder	6	AZ Tucson	76	55,203	56,414	1211	2.19
12	CA remainder	7	AZ remainder	228	151,493	151,815	322	0.21
			Total	1134	695,714	710,567	14,853	2.13

[a] % Change = (*D*/before value) * 100.

miles. The most impacted O–D pair is the "Los Angeles to Phoenix", combination, which shows an 11.88% increase in path-miles. Table 3 shows which region is most impacted from the bridge disruption in terms of increased miles traveled as described in Fig. 1. Note that the miles shown in the Table only provide a general representation of the impact.

These increased distances are multiplied by the shipping cost per mile to estimate increased shipping cost by USC Sector. The shipping cost per mile was calculated from the costs for purchasing truck mode services as a fraction of the total input value in California, also by USC sector. We used raw data from the 2001 IMPLAN commodity balance sheet for California to estimate these values. This permits us to calculate the values in the columns "Purchase of Truck Service" (PTS) and "Total Input Value" (TIV) in Table 1. These give ratios corresponding to the shipping cost per unit value by industry, shown in the column "Truck Cost per Unit Value" (TCUV).

The baseline shipping values using truck services are multiplied by the TCUV ratios. This produces the estimated truck service cost for each shipping value. Also, using baseline miles between the network centroids in California and Arizona, we compute the truck services cost associated with each shortest path. The top three sectors with respect to average truck service costs per mile are USC Sectors 16 (logs and other wood in the rough and wood products), 15 (plastics and rubber), and 8 (nonmetallic minerals). These sectors have average truck service costs ranging from $53 to $119 per mile.

Baseline shipping values produce baseline shipping costs. Changing miles traveled due to the disruption increases shipping costs. This perspective is most valid for a short-run analysis. The final results are the changes in shipping costs obtained relative to the baseline conditions. These values appear in the column labeled "Δcost" in Table 4. Note the values in the Table 4 are matched to "Calculate total increased shipping cost by 47 USC Sectors" in Fig. 1, and are used as inputs of the price-type input–output model. Overall the increased shipping cost relative to the baseline case was 0.16% for the I10 scenario, and ranged from 0.02% to 0.33% depending on the industry.

In the short run, the increased shipping costs will be passed through as price increases. The increased costs will boost product prices. Table 5 shows the results of applying the price-type input–output model as well as the demand-driven NIEMO in Fig. 1. The column labeled "Amounts Resulting from Price Increases" in Table 5 shows the increased prices by USC Sector because of increased shipping costs. These increased product prices reduce expenditures by final users. We assumed that the increased prices will decrease the total final demands by Arizona final users by a corresponding amount. Using the demand-driven version of NIEMO, we calculated the state-by-state economic impacts resulting from the decreases in final demands specific to Arizona. See the column labeled "Decreases in expenditures in Arizona." The total decrease in expenditures of $30 million accounted for $62 million in total output losses nationwide.

Table 6 shows the associated state-by-state economic impacts via the demand-driven NIEMO. As expected, Arizona is the most seriously affected state. The adjacent states, California and Texas, show over $1 million in economic losses from the bridge services

Table 4
Shipping costs: California to Arizona.

		Baseline			Scenario		
USC Sector	Description	Value of Shipping ($M)	Avg. truck cost per mile[a] ($/mile) ①	Total shipping cost ($M) ②	Total shipping cost ($M) ③	Δcost ($M) ④ = ③ − ②	Change[b] ④/① (%)
USC01	Live animals and live fish and meat, fish, seafood, and their preparations	272.02	9.63	4.73	5.15	0.4139	0.15
USC02	Cereal grains and other agricultural products except for Animal Feed	540.91	16.79	8.33	9.05	0.7167	0.13
USC03	Animal feed and products of animal origin, n.e.c.	296.81	17.87	8.85	9.61	0.7618	0.26
USC04	Milled grain products and preparations, and bakery products	0.15	0.00	0.00	0.00	0.0001	0.07
USC05	Other prepared foodstuffs and fats and oils	8.99	0.40	0.17	0.19	0.0183	0.20
USC06	Alcoholic beverages	275.24	9.54	4.84	5.22	0.3749	0.14
USC07	Tobacco products	0.00	0.00	0.00	0.00	0.0000	-
USC08	Nonmetallic minerals (monumental or building stone, natural sands, gravel and crushed stone, n.e.c.)	1278.66	53.23	27.87	30.00	2.1204	0.17
USC09	Metallic ores and concentrates	158.44	6.86	2.93	3.28	0.3484	0.22
USC10	Coal and petroleum products (Coal and Fuel oils, n.e.c.)	278.46	1.62	0.78	0.85	0.0665	0.02
USC11	Basic chemicals	214.95	6.69	3.44	3.67	0.2267	0.11
USC12	Pharmaceutical products	157.17	1.33	0.68	0.73	0.0584	0.04
USC13	Fertilizers	0.27	0.01	0.01	0.01	0.0002	0.07
USC14	Chemical products and preparations, n.e.c.	147.05	5.54	2.82	3.07	0.2504	0.17
USC15	Plastics and rubber	1175.26	68.62	34.55	37.34	2.7825	0.24
USC16	Logs and other wood in the rough and Wood products	2298.11	113.88	58.37	63.03	4.6576	0.20
USC17	Pulp, newsprint, paper, and paperboard and Paper or paperboard articles	144.54	7.76	3.77	4.09	0.3164	0.22
USC18	Printed products	819.46	26.90	13.36	14.49	1.1325	0.14
USC19	Textiles, leather, and articles of textiles or leather	2.87	0.05	0.04	0.04	0.0015	0.05
USC20	Nonmetallic mineral products	359.99	30.77	15.77	16.94	1.1708	0.33
USC21	Base metal in primary or semi-finished forms and in finished basic shapes	1106.65	47.72	25.23	27.16	1.9252	0.17
USC22	Articles of base metal	214.78	5.89	2.96	3.20	0.2355	0.11
USC23	Machinery	254.93	4.53	2.17	2.36	0.1978	0.08
USC24	Electronic and other electrical equipment and components, and office equipment	295.49	1.11	0.56	0.61	0.0459	0.02
USC25	Motorized and other vehicles (including parts)	232.59	6.40	3.19	3.45	0.2621	0.11
USC26	Transportation equipment, n.e.c.	339.39	6.60	3.43	3.67	0.2375	0.07
USC27	Precision instruments and apparatus	771.20	5.16	2.62	2.83	0.2077	0.03
USC28	Furniture, mattresses and mattress supports, lamps, lighting fittings, and illuminated signs	1.08	0.03	0.02	0.02	0.0005	0.05
USC29	Miscellaneous manufactured products, Scrap, Mixed freight, and Commodity unknown	268.65	4.76	2.34	2.53	0.1904	0.07
Total		11914.12		233.83	252.56	18.7208	0.16

[a] *Ave.* truck cost per mile denotes average cost per mile for shipping from California to Arizona using trucks. In application, we used the truck cost per mile for each route between CA to AZ to estimate the increased cost.

[b] % Change = (Δcost/shipping value) * 100.

eliminated in the I10 scenario. The indirect economic impacts are spread throughout the nation. Even though we estimated approximately $62 million direct and indirect economic impacts based on the I10 bridge scenario, this is only a partial loss. We also have to consider analysis of shipping movements to other destinations using the I10 route. An expanded area analysis will increase the economic impacts considerably, and state-by-state impacts may be different.

7. Conclusions and discussion

We have constructed the TransNIEMO prototype and run an initial test involving trade between California and Arizona. This research examines transportation network and economic impact analysis based on experimental scenarios. We specified an interstate network system based on FHWA and FAF nation-wide freeway network data, and distributed freight demand from economic centroids onto the network system. We calculated the state-by-state economic impacts resulting from increased shipping costs accruing as a consequence of transportation service disruptions associated with the elimination of key bridges.

Further extensions require further elaboration of the nation-wide network. This first-step experimental analysis of state-to-state economic impacts includes several restrictive assumptions. However, once the nation-wide transportation network system model is completed, we can estimate more precise impact results and results for scenarios involving network links in other States. This will permit us to complete spatially disaggregated economic impact analyses for case studies involving any natural disaster or hypothetical terrorist attacks on critical infrastructure. Also, TransNIEMO can be made more accurate by adding more spatial detail to the model. For example, rerouting across other regions will require the consumption of additional gas, food, etc. because of longer driving times. In the future, scenarios will be developed to introduce this additional behavior into TransNIEMO.

The most important next step is to improve the model's computability. The proof-of-concept exercise described here shows that NIEMO can be extended into a TransNIEMO formulation and that the model can be used to compute widely distributed economic impacts associated with local disruptions in infrastructure services. However, the model is computationally difficult in its present form. The example summarized here could be expanded to include a sub-national region consisting of several states. Also,

Table 5
Economic impacts: price and total impacts by industry sector ($millions).

USCsec.	Description	Amounts resulted from price increases	Decreases in expenditure of Arizona	Total economic impacts by sector
USC01	Live animals and live fish and meat, fish, seafood, and their preparations	0.414	0.519	0.825
USC02	Cereal grains and other agricultural products except for animal feed	0.717	0.732	1.029
USC03	Animal feed and products of animal origin, n.e.c.	0.762	0.791	1.000
USC04	Milled grain products and preparations, and bakery products	0.000	0.079	0.135
USC05	Other prepared foodstuffs and fats and oils	0.018	0.194	0.715
USC06	Alcoholic beverages	0.375	0.384	0.610
USC07	Tobacco products	0.000	0.000	0.000
USC08	Nonmetallic minerals (monumental or building stone, natural sands, gravel and crushed stone, n.e.c.)	2.120	2.127	2.447
USC09	Metallic ores and concentrates	0.348	0.364	0.657
USC10	Coal and petroleum products (coal and fuel oils, n.e.c.)	0.067	0.108	1.619
USC11	Basic chemicals	0.227	0.243	0.706
USC12	Pharmaceutical products	0.058	0.076	0.117
USC13	Fertilizers	0.000	0.007	0.097
USC14	Chemical products and preparations, n.e.c.	0.250	0.339	1.086
USC15	Plastics and rubber	2.783	3.002	4.161
USC16	Logs and other wood in the rough and wood products	4.658	5.031	7.775
USC17	Pulp, newsprint, paper, and paperboard and Paper or paperboard articles	0.316	0.341	1.133
USC18	Printed products	1.133	1.183	1.375
USC19	Textiles, leather, and articles of textiles or leather	0.002	0.040	0.288
USC20	Nonmetallic mineral products	1.171	1.308	2.015
USC21	Base metal in primary or semi-finished forms and in finished basic shapes	1.925	2.068	4.032
USC22	Articles of base metal	0.236	0.306	1.093
USC23	Machinery	0.198	0.326	1.331
USC24	Electronic and other electrical equipment and components, and office equipment	0.046	0.131	1.187
USC25	Motorized and other vehicles (including parts)	0.262	0.424	0.821
USC26	Transportation equipment, n.e.c.	0.238	0.313	0.371
USC27	Precision instruments and apparatus	0.208	0.238	0.328
USC28	Furniture, mattresses and mattress supports, lamps, lighting fittings, and illuminated signs	0.001	0.268	0.369
USC29	Miscellaneous manufactured products, scrap, mixed freight, and commodity unknown	0.190	0.236	0.830
USC30	Utility	0.000	0.078	0.830
USC31	Construction	0.000	4.532	4.713
USC32	Wholesale trade	0.000	0.360	3.038
USC33	Transportation	0.000	0.150	1.717
USC34	Postal and warehousing	0.000	0.029	0.419
USC35	Retail Trade	0.000	0.325	0.979
USC36	Broadcasting and information services*	0.000	0.110	0.778
USC37	Finance and insurance	0.000	0.114	1.359
USC38	Real estate and rental and leasing	0.000	0.551	2.239
USC39	Professional, scientific, and technical services	0.000	0.124	2.298
USC40	Management of companies and enterprises	0.000	0.037	0.731
USC41	Administrative support and waste management	0.000	0.127	0.963
USC42	Education services	0.000	0.017	0.047
USC43	Health care and social assistances	0.000	0.746	0.807
USC44	Arts, entertainment, and recreation	0.000	0.044	0.149
USC45	Accommodation and food services	0.000	0.452	0.739
USC46	Public administration	0.000	0.153	0.222
USC47	Other services except public administration	0.000	0.484	2.000
Total		18.721	29.611	62.180

another challenge involves model validation. In all such exercises, the modelers' *ceteris paribus* assumption must be discarded. This is why only immediate short-term performance changes should be studied in the TransNIEMO type applications.

The model's complexity is apparent if the formulation is compared to corresponding metropolitan level models. Urban transportation planning models might include in the neighborhood of 3000 traffic analysis zones, whereas at first inspection TransNIEMO appears to have only 114. At the urban level, zone centroids are virtual locations that are connected to network links to provide a mathematical mechanism for loading transportation demand onto the network. Each centroid is connected to a small number of physical links. In TransNIEMO, economic centroids are the centers of gravity for national transportation demands associated with an MSA or similar region. Relating the spatial identity of an economic centroid to the entire metropolitan network is an abstract objective. Imposing these demands on the network at physical locations corresponding to a 10% sample of physical intersections still produces a highly redundant network in the vicinity of economic centroids. This makes it unlikely that loss of discrete infrastructure capacity in urban areas will produce significant changes in path flows, and this is a realistic result. Certain exceptions apply, primarily bridges crossing wide bodies of water.

This level of redundancy has advantages but is likely unnecessary. The current model represents urban networks in too much detail. This combined with a traffic assignment method that requires pre-enumeration of shortest paths between numerous network centroids produces a computation burden that can be substantially diminished. Exactly how is a question for additional research, but the objective is certainly achievable. The high

Table 6
Economic impacts by state ($millions).

State	Direct impact	Indirect impact	Total impact
AL	0.0000	0.1511	0.1511
AK	0.0000	0.0256	0.0256
AZ	29.6113	16.0553	45.6666
AR	0.0000	0.2117	0.2117
CA	0.0000	3.9340	3.9340
CO	0.0000	0.1961	0.1961
CT	0.0000	0.0759	0.0759
DE	0.0000	0.0116	0.0116
DC	0.0000	0.0061	0.0061
FL	0.0000	0.7744	0.7744
GA	0.0000	0.1613	0.1613
HI	0.0000	0.0189	0.0189
ID	0.0000	0.1428	0.1428
IL	0.0000	0.4560	0.4560
IN	0.0000	0.3610	0.3610
IA	0.0000	0.1377	0.1377
KS	0.0000	0.1158	0.1158
KY	0.0000	0.1571	0.1571
LA	0.0000	0.1707	0.1707
ME	0.0000	0.0190	0.0190
MD	0.0000	0.0711	0.0711
MA	0.0000	0.1213	0.1213
MI	0.0000	0.3238	0.3238
MN	0.0000	0.2419	0.2419
MS	0.0000	0.0945	0.0945
MO	0.0000	0.1915	0.1915
MT	0.0000	0.1103	0.1103
NE	0.0000	0.0811	0.0811
NV	0.0000	0.1583	0.1583
NH	0.0000	0.0342	0.0342
NJ	0.0000	0.1706	0.1706
NM	0.0000	0.1377	0.1377
NY	0.0000	0.2925	0.2925
NC	0.0000	0.1695	0.1695
ND	0.0000	0.0124	0.0124
OH	0.0000	0.3506	0.3506
OK	0.0000	0.1191	0.1191
OR	0.0000	0.6124	0.6124
PA	0.0000	0.2371	0.2371
RI	0.0000	0.0244	0.0244
SC	0.0000	0.1029	0.1029
SD	0.0000	0.0184	0.0184
TN	0.0000	0.1592	0.1592
TX	0.0000	1.6092	1.6092
UT	0.0000	0.1083	0.1083
VT	0.0000	0.0129	0.0129
VA	0.0000	0.0899	0.0899
WA	0.0000	0.5112	0.5112
WV	0.0000	0.0541	0.0541
WI	0.0000	0.2863	0.2863
WY	0.0000	0.0176	0.0176
US total	29.61	29.71	59.32
Rest of world	0.00	2.8620	2.86
World total	29.61	32.57	62.18

number of alternative shortest paths being computed share many long-haul links in common. However, the current study was focused on state border bridge disruptions. Consequently, there is little to be gained from adding details to MSA-level networks once sufficient capacity has been represented in these locations to ensure transshipment of interstate flows, or that identify the relatively small number of high design facilities essential to supporting transshipment flows. Yet, further work on TransNIEMO requires an equilibrium cost flow approach if applied to network disruptions within a metropolitan area.

TransNIEMO is built to address research questions that include anticipating and avoiding the costs of capacity losses. This contrasts with the standard metropolitan-level objective of predicting level of service as a function of fixed supply and increasing demand, and ensures a relatively high set of computational requirements. TransNIEMO is to some extent a network design exercise in which the decision is not to add capacity, but to protect existing capacity, possibly by adding redundancy. Any application arena in which the physical configuration of a large transportation network is being updated and flows redistributed will necessarily be computationally expensive to model.

Our initial efforts to specify TransNIEMO focused on data availability, use, and reconciliation and the higher level question of how to translate increased transportation costs into disaggregated economic impacts. Once we were convinced we had sufficient computing capacity to allow us to test the basic framework for the approach and provide a proof of concept, computational efficiency took a back seat to the larger question of how transportation costs filter through an economy represented in spatial detail. As a result, the current research model can be subjected to considerable computational improvement, and this will allow it to be applied more readily to the analysis of a wider array of alternatives.

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