

**ADDING A FREIGHT NETWORK TO A NATIONAL
INTERSTATE INPUT-OUTPUT MODEL:
IMPLICATIONS 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. And ever since the terrorist attacks of 9/11, there has been increasing concern over the extent to which an attack on infrastructure could cause serious economic disruption. This research develops a model by which the economic consequences of an attack on any major element of the highway network can be analyzed. We do this by adding a freight network to a national multiregional economic impact model and making freight traffic flows endogenous. We base our approach on the National Interstate Economic Model (NIEMO) and refer to the elaboration as TransNIEMO (Transportation network and the National Interstate Economic Model). The new model enables us to study the state-specific and industry-specific economic impacts of any 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 U.S.

1. Introduction

The construction of canals and railroads in the 19th century connected the central lowlands of the U.S. with the outer world, facilitating regional specialization, trade and economic growth and establishing the U.S. as a major supplier of agricultural production to much of the world (U.S. Department of Transportation, Federal Highway Administration, 2004). A century later, President Eisenhower saw the importance of a national inter-connected highway system.. Since then the Interstate Highway System has served most of the nation's freight movements, facilitating continuing regional economic specialization and long-term the development of the U.S 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 between regions is essential for making investment plans throughout the economy. The same holds for investments by the various public agencies that manage the highway network system.

Improved analysis is now possible because the Federal Highway Administration (FHWA) has integrated various shipments data into the Freight Analysis Framework (FAF). The FAF contains commodity flows among sub-state regions (U.S. DOT, FWHA, 2006a). However, the FAF data only provide origin-destination shipment data among these sub-state regions and exclude data on the highway networks along which freight flows move. While FAF was the basis of important capacity information, our operational multi-regional input-output model, the National Interstate Economic Model (NIEMO) was the source of interstate shipment demand data. Our research plan was to use both tools to find ways to allocate 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.

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 part of METRANS' focus: We study commercial goods movement and international trade in metropolitan areas and its physical economic cost impact in any case of terrorist attack. Even though this research is initially a California experiment, the success of our proof-of-concept application now makes it possible to broaden tests and applications of TransNIEMO to the rest of the U.S.

While NIEMO is spatially disaggregated only to the state level, the transportation nodes for each mode are the major metropolitan areas, which are the dominant centers of economic activity (based on U.S Census employment data). Furthermore, in most states there is one or more major metropolitan area: The non-metropolitan regions in selected cases also account for a high proportion of state gross domestic product and freight OD movements.

In previous work (Gordon et al. (2006), computing the indirect and induced effects of impacts associated with capacity losses at the twin ports of Los Angeles-Long Beach showed that two-thirds of the impacts leak outside the region. Without a model such as NIEMO, we would have no idea of where those leakage effects might occur. In this sense, the current effort to integrate a major transportation network system with NIEMO links interindustry transactions of freight movements between the nation and California. 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. 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 thirty 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, Research and Innovative Technology Administration & Bureau of Transportation Statistics, 2006b). 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 five-year cycle updates of 1997 and 2002, some user groups have not been satisfied with its content details when they apply the data to their specific projects (USDOT, RITA & BTS, 2005). The most commonly addressed weaknesses of 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. 2007, Giuliano, 2007). Capelle (2000) showed that the CFS estimates only cover less than 75 percent of all the freight tons moved annually in the U.S. 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. (2007b) managed to construct 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, they 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 and Gordon, 2005).

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.

To overcome the shortcomings of CFS, efforts have been made to combine it with other data sources. To further understand freight activity, the U.S. Department of Transportation created the Freight Analysis Framework (FAF) in 2002. FAF is a comprehensive database for policy analysis (U.S. DOT, FHWA, 2002a) 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 (U.S. DOT, FHWA, 2006a). 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 (U.S. DOT, FHWA, 2006b). Unfortunately, there are still discrepancies with other data sources due to the inclusion of service values into the data for commodity sectors.

In addition to government efforts, various research groups have also tried to create better datasets. 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 Zone (TAZ), Waterborne Commerce of the U.S. (WCUS) and airport data from RAND. Although this work was limited to the highway network within one area, the results suggested the potential for expanding the approach to other metropolitan areas.

It is also important to note the availability of highway network data. Freight transportation is overwhelmingly an interstate activity, accounting for 73 percent of total ton-miles (U.S. DOT, FHWA and BTS, 2002). The data for this research is primarily related to the highway . However, rail, air, and water networks cannot be ignored (Yu, 2006), and we plan to address integrating the other modes in future research. The National Highway Planning Network (NHPN) has about 452,000 miles of roads, of which the Freight Analysis Framework (FAF) contains 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 2,125 miles of urban streets and rural minor arterials.

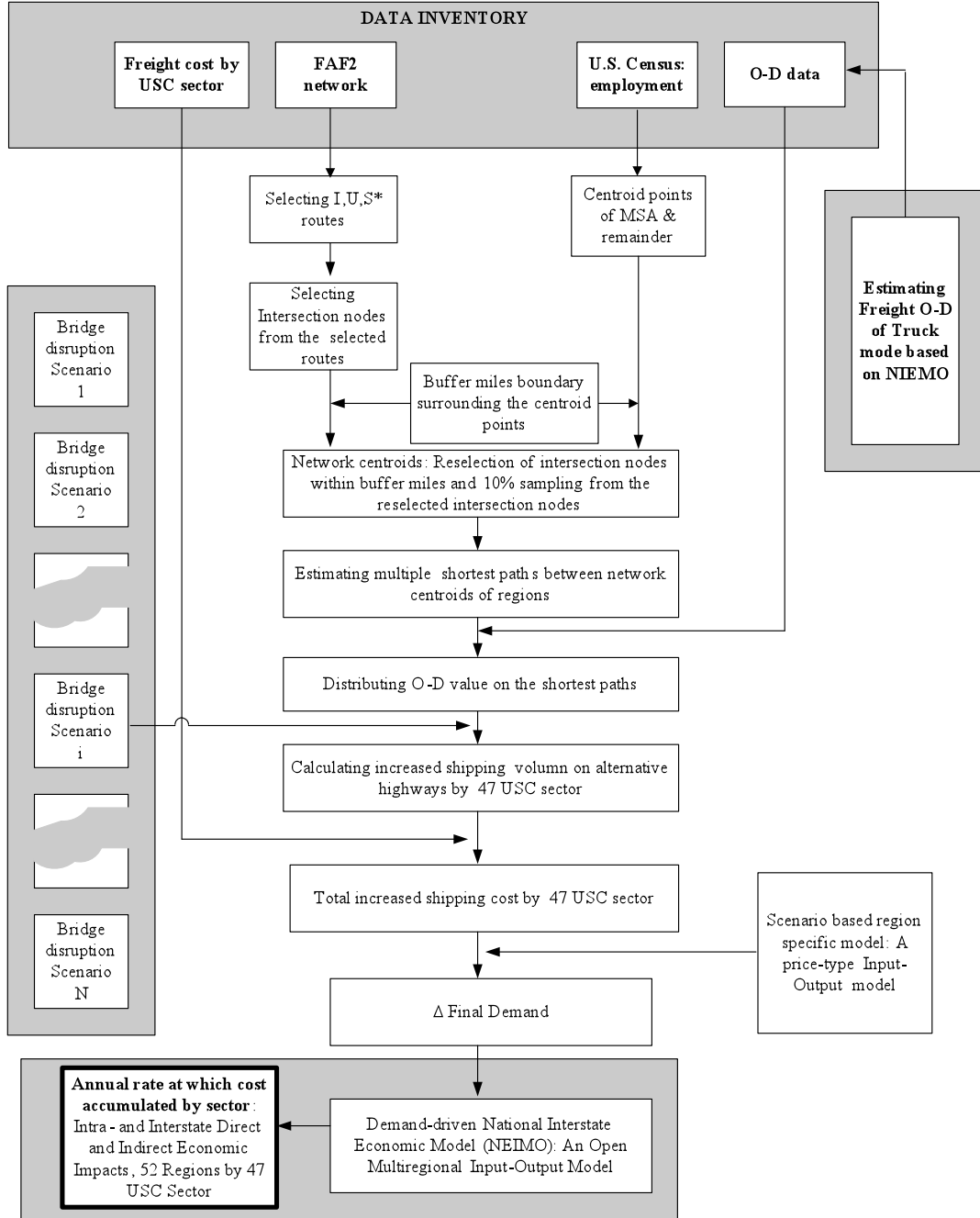
4. Methodology

This application of TransNIEMO involves two major steps:

- i. Estimation of increased costs due to a disaster based on the constructed highway network system, and
- ii. State-by-state economic impact analysis applying NIEMO due to decreased household consumption, resulting from price increase of 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 bridge. Figure 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 one-year disruption. The linearity of the models makes it possible to study any period.

We established the basic dataset by obtaining the national highway network data for Freight Analysis Framework, available via download from the Federal Highway Administration (FHWA). We pruned the small arterials and local by-ways because this reduced computational burdens without sacrificing realism. Most truck drivers delivering freight minimize costs by using higher design facilities such as the Interstate Highways (for example, I5, I10, I405, etc.), U.S. Route (for example, US101, US395, etc.), or State Route (for example, SR-11, SR-125, etc.) to the maximum extent possible. To conduct the pruning procedure, we implemented spatial selection using the GISDK function of TransCAD software. We then built a base national map for this application that includes only the three major highway networks.



- I: Interstate highway, U: U.S. Route, and S: State Route.

Figure 1 TransNIEMO: Data and Modeling Process

Because the sectorization scheme used in NIEMO does not break out truck use information, we established the proportions in the OD data correspond to the truck mode based on the FAF 2.2 data. Trade information from NIEMO was multiplied to the proper proportions and then truck OD requirements computed. This was to exclude the services sector information in the FAF 2.2 OD 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. Our examples involving California, Arizona, and Nevada thus do not include any freight gateways (U.S. DOT, FHWA, 2006b). The sub-state regions are largely equivalent to Metropolitan Statistical Areas (MSAs) and remainder non-MSAs.

We generated geographical centroids for the 114 sub-state regions to combine the truck OD data with a GIS map file. However, because the centroids do not reflect the locations of economic activities associate with each region, we adjusted the geographic centroids using city-level employment figures available from the U.S. Census Bureau. The adjusted economic centroids better represent the economic activities in the MSAs and 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 extremely 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 solution if network disruptions are sufficient to isolate supply or demand locations.

This is not an unusual problem modeling user behavior in networks. The simplest meaningful way to predict economic behavior is to assume perfect information and rationality on the part of economic agents. This is usually a reasonable and useful approach, and is so 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 cost, 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 second shortest paths between sub-states regions, we developed an approach for selecting and associating nodes representing physical intersections on the highway network with OD pairs. Estimated shortest paths will generally 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 starting points of truck freight shipments, we defined buffer-zone boundaries 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 greatest level of spatial detail associated with the transportation network.

Table 1 shows the approach to defining the buffer-mile boundaries for sub-state regions and the number of network centroids by region. For the MSA regions, we applied 35-mile buffer boundaries. For the reminder areas, we applied several criteria: 35, 50, 75, 100, and 200 miles of buffer boundaries, combining geographic size of each MSA and mathematical analysis as described in Table 1. For the special cases of Massachusetts and Maryland, we adapted 100-mile boundaries because of peculiar geographic shapes.

<Table 1, here>

These criteria identify and 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 percent of the network centroids associated with each economic centroid. A study about generalized coefficients of buffer miles by region is on our research agenda. Figure 2 shows that this approach effectively represents the original set of network centroids. This 10 percent sample of network centroids can reasonably be expected to define representative sets of alternative paths to accommodate freight flows between economic centroids.

<Figure 2, here>

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 OD pairs. The OD volumes on the network links are determined along with the equilibrium cost link flows. In the case of the FAF OD data, however, the standard equilibrium cost flow model is inappropriate because interurban and interstate line-haul costs dominate congestion costs. Finding shortest paths between OD pairs becomes a combinatoric problem. In this research, we enumerate the number of paths between two substate regions by defining paths between all possible network centroid pairs involving the two regions. We distributed truck OD 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. The cumulative volume of freight so distributed on a highway is considerably less than the capacity of the highway links.

To demonstrate our approach we simulated a plausible scenario: We eliminated a critical bridge that plays a key role connecting California to adjacent states. Due to loss of the bridge, major alternative highways have to be identified to accommodate the affected freight volumes. Critical bridges on six major routes are shown in Figure 3: These are part of Interstate Highways 5, 8, 10, 15, 40, and 80 (I5, I8, I10, I40, and I80, respectively).

<Figure 3, here>

The increased miles associated with shipping commodities before and after removing the bridge from the network are used to estimate increased trucking costs for each industry sector. After calculating truck costs per mile by industry sector, we multiplied these costs by the increased miles travelled to estimate the increased cost in each industry. The increased shipping cost, in turn, drives increased prices, and induces a decrease in consumer expenditures. Modeling this effect is approached as follows. With the assumption that all increased truck costs are passed forward as price increases, we utilized a supply-driven I-O model. Dietzenbacher (1997) showed

that the supply-driven I-O model is to the more meaningful formulation for estimating price increases than the Leontief price I-O model when *absolute* costs in 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. Application

The goals of this research were not merely to develop an appropriate database resource for adding a transportation network for NIEMO (TransNIEMO), but 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 the induced final demand changes in any location within the national economy – as well as the transportation and output impacts in each state following 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.

For future research, the number of potential applications for this approach is almost limitless. A particularly useful example would involve Los Angeles-Long Beach ports, primarily because of the spatial reach of their economic importance throughout the national (and indeed the global) economy, and their enormous transportation implications for both the regional and national economy. There are many specific scenarios within this framework, but in the view of the long-term trend involving trade deficits, an interesting example might be to model an exogenous increase in imports balanced by an exogenous decrease in exports within individual sectors. We could then explore the implications of such a scenario for both the national and regional highway network.

However, largely because of its relevance to homeland security, we selected a scenario based on eliminating access to highway bridges. We selected freight destinations in two states outside California: Nevada and Arizona. In response to the disruption scenario for the I15, most of the

freight flows on I15 moved to I40. The bridge disruption scenario for the I80 caused most of the freight flows on the highway move to an adjacent highway, U.S Route 50. Figures 4 and 5 show these movements graphically. Alternative shortest paths (coded 0_1 and 0_2) are highlighted in the circled areas.

<Figure 4, here>

<Figure 5, here>

Table 3 shows the detailed changes in the dollar value of shipping on highways from California to Nevada due to the disruption of flows that would otherwise be on I80 or I15. In Table 3, columns 1 (I15) and 10 (I80) show large decreases in the number of available paths (many paths use these routes) and in the dollar value of shipping along these paths. Similarly, the alternative routes identified in columns 0_1, 0_2, and 9 show increases in paths and shipping values.

<Table 3, here>

To complete a more detailed impact analysis, we performed calculations for the disruption scenario on the I10 for the case of California and Arizona. This case is one of the possible scenarios as shown in Table 2. Figure 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 in the highlighted circle. These results can be examined in detail in Table 4, which shows the 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. While the number of paths and dollar value shipping associated with I10 decreased 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.

<Table 4, here>

6. Results

If a major bridge linking California and Arizona on the I10 is eliminated, most shortest-path travel would move to the adjacent S-62 freeway. Based on this disruption scenario of I10 and the diversion to shortest paths, we estimated the increased distance that the freight is shipped. Table 5 shows increased miles between origins and destinations. The last column “Change in Miles,” shows the percentage increase in path miles, that is, % Change. The most impacted OD pair is the “Los Angeles to Phoenix,” combination, which shows an 11.88 percent increase in path-miles.

<Table 5, here>

The increased distances were 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 6. These give ratios corresponding to the shipping cost per value by industry, shown in the column “Truck Cost per Value” (TCV).

<Table 6, here>

The baseline shipping values using truck services are multiplied by the TCV 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 computed the miles of 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 & 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 7. Overall the increased shipping cost relative to the baseline case was 0.16 percent for the I10 scenario, and ranged from 0.02 to 0.33 percent depending on the industry.

<Table 7, here>

In the short run, the increased shipping costs will be passed through as price increases. The increased costs will boost product prices. Table 8 shows the increased prices by USC Sector due to the increased shipping costs in the column labeled “Amounts Resulted from price increases.” [***Should be “Quantities Resulting from Price Increases.”]. 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 expenditure of Arizona.”. The total decrease in expenditures of \$30 million accounted for \$62 million in total output losses nationwide.

<Table 8, here>

Table 9 shows the associated state-by-state economic impacts. 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 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 and may be very different.

<Table 9, here>

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 disaggregate economic impact analyses for case studies involving any natural disaster or hypothetical terrorist attacks on critical infrastructure.

The most important next step is to improve the model's computability. This proof-of-concept exercise shows that NIEMO can be extended into a TransNIEMO formulation and that the model can be exercised to compute widely distributed economic impacts associated with local disruptions in infrastructure services. However, the model is computationally intractable in its present form. The example summarized here could be expanded to include a sub-national region consisting of several states, but desktop computational resources are not sufficient to permit a fully national implementation of the model.

The model's complexity is apparent the formulation is compared to corresponding metropolitan level models. Urban transportation planning models might include in the neighborhood of 3,000 traffic analysis zones differences, 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 entire metropolitan network is an abstract objective. Imposing these demands on the network at physical locations corresponding to a 10 percent sample of physical intersections still produces a highly redundant network in the vicinity of economic centroid. 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 number of alternative shortest paths being computed share many long-haul links in common. 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 identifies the relatively small number of high design facilities essential to supporting transshipment flows.

The fact the research questions TransNIEMO is built to address include, principally, anticipating and avoiding the costs of capacity losses rather than the standard metropolitan level objective of prediction level of service as a function of fixed supply and increasing demand 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 never be computationally cheap 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 disaggregate economic impacts. Once we were convinced we had sufficient computing capacity to allow us to test the basic framework for 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 used more readily for analysis of a wider array of alternatives.

Table 1. Buffer radius by size of remainder areas

State	Area size	Miles	Number of Network centroid (10% sample)	State	Area size	Miles	Number of Network centroid (10% sample)
RI	1,045	35	13	VA	28,094	75	58
NJ	1,153	35	37	NY	29,149	75	106
DE	1,981	35	13	ME	31,173	75	13
CT	2,738	35	43	TN	33,793	75	43
MA ¹	3,966	100	43	NC	34,257	75	52
MD ¹	4,882	100	37	KY	36,821	75	29
HI	5,736	35	-	PA	37,330	75	66
NH	9,238	50	11	LA	39,400	75	27
VT	9,596	50	9	FL	40,560	75	62
WV	24,205	75	13	AL	44,260	100	33
SC	24,739	75	50	IL	46,241	100	79
OH	25,710	75	71	MI	47,252	100	43
IN	27,634	75	35	MS	47,700	100	24
GA	48,325	100	85	KS	79,341	200	57
AR	53,147	100	24	ID	83,393	200	13
WI	54,052	100	70	NV	84,246	200	14
IA	56,181	100	32	AZ	90,225	200	21
OK	56,632	100	31	OR	92,270	200	27
WA	56,905	100	25	CO	94,864	200	35
MO	59,534	100	38	WY	97,634	200	16
UT	66,240	200	26	CA	104,473	200	54
ND	70,484	200	25	NM	121,620	200	22
MN	72,449	200	60	MT	146,646	200	13
SD	76,956	200	22	TX	219,897	200	98
NE	77,249	200	36	AK	572,122	200	-

Notes: 1. Due to the narrow and long shape of these regions, 100 mile boundaries are applied for the remainders of MA and MD.

M_i of MA and MD is 63.0 and 69.9 respectively.

2. Each buffer radius is selected as follows:

$$M_i = \frac{\sqrt{S_i}}{2},$$

where i = an index identifying each MSA remainder area and S_i is the size each region.

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

3. Hawaii (HI) and Alaska (AK) are excluded from the current version of TransNIEMO, but included in NEIMO.

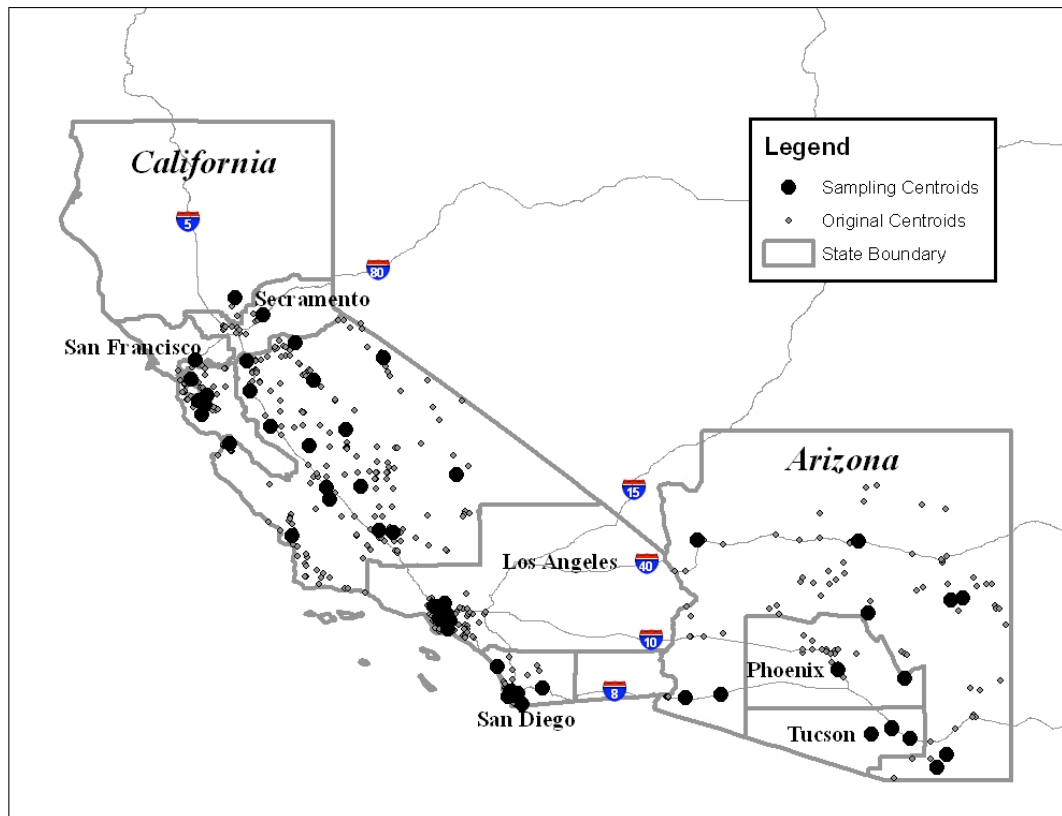


Figure 2. Sampled Network Centroids: CA and AZ

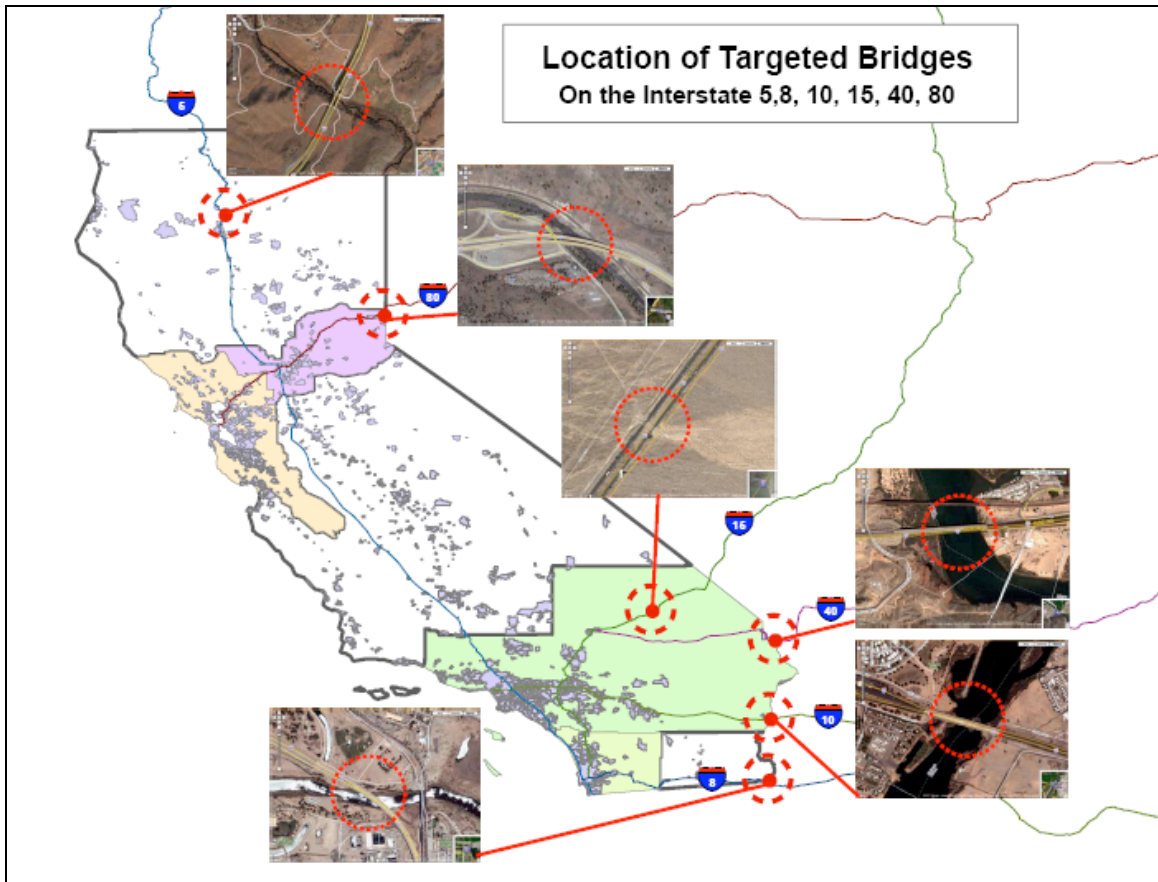


Figure 3. Location of Scenario Bridges on Interstate Freeways

Table 2. Candidate bridge destruction scenarios

		(Interstate) Highway Combinations Affected						
		I10	I15	I18	I10+I15	I10+I18	I15+I18	I10+I15+I80
Destinations	AZ	O						
	NV		O	O			O	
	AZ+Nv	O	O	O	O	O	O	O

Note: Shading identifies the scenario cases summarized in Table 4.

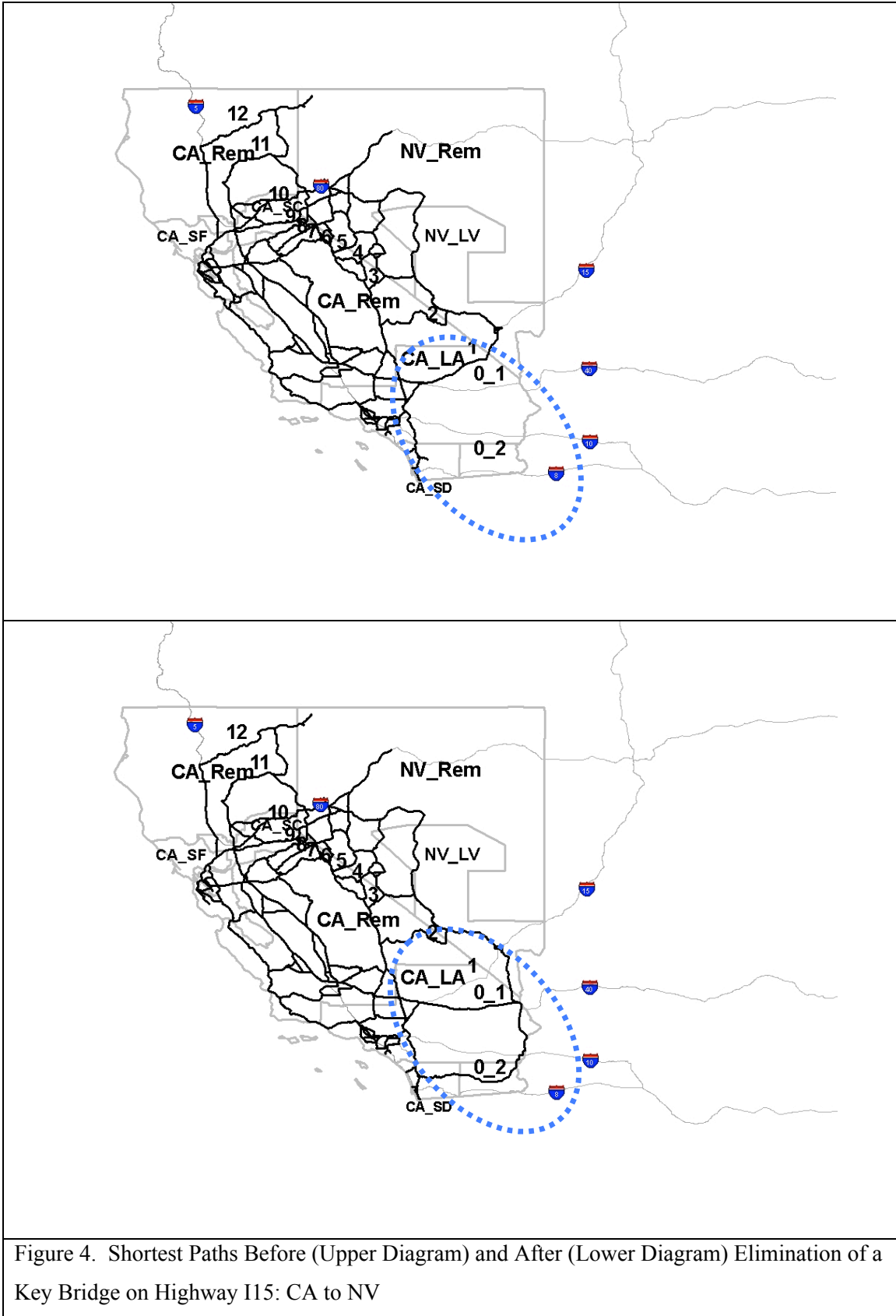
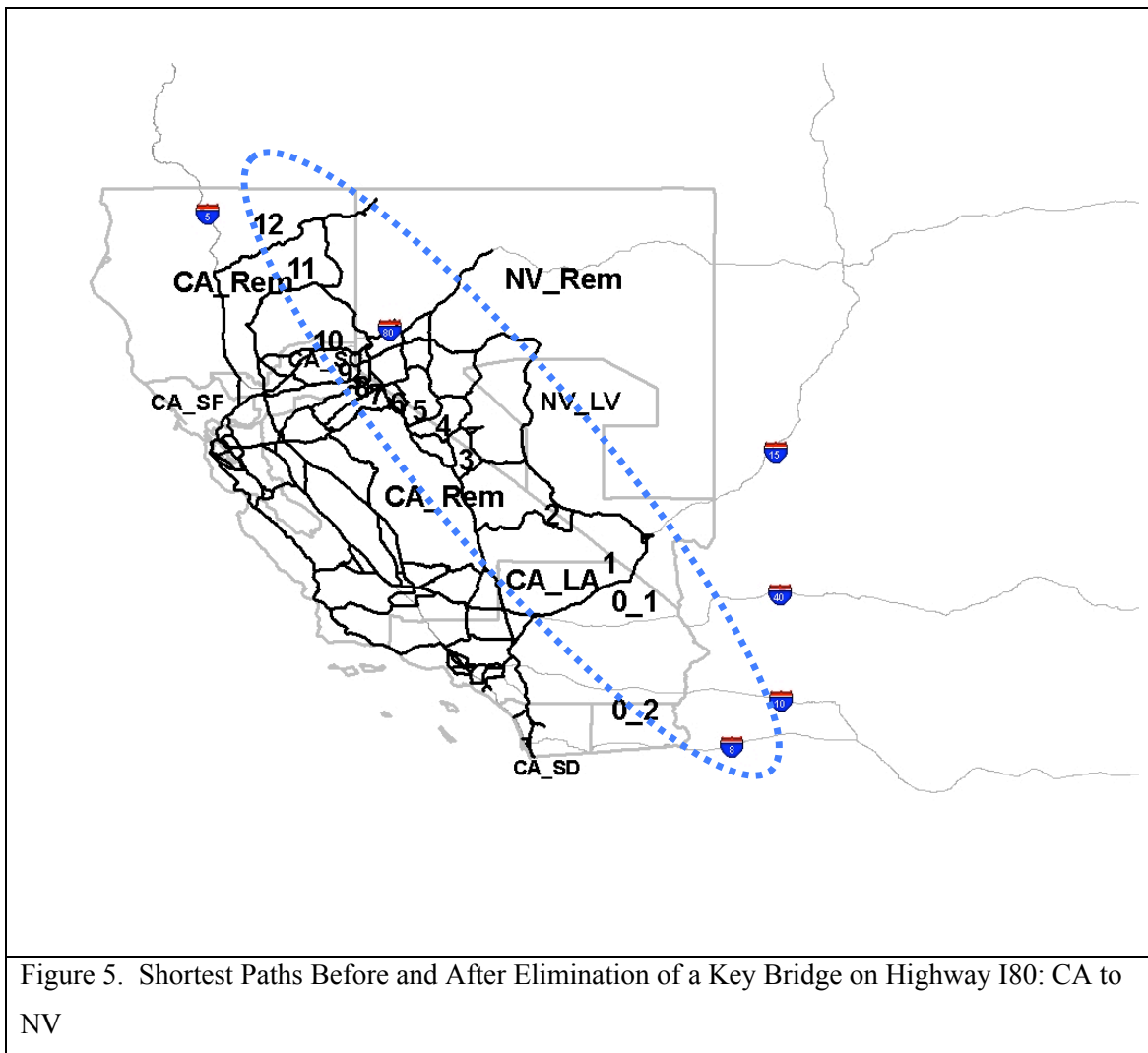


Figure 4. Shortest Paths Before (Upper Diagram) and After (Lower Diagram) Elimination of a Key Bridge on Highway I15: CA to NV



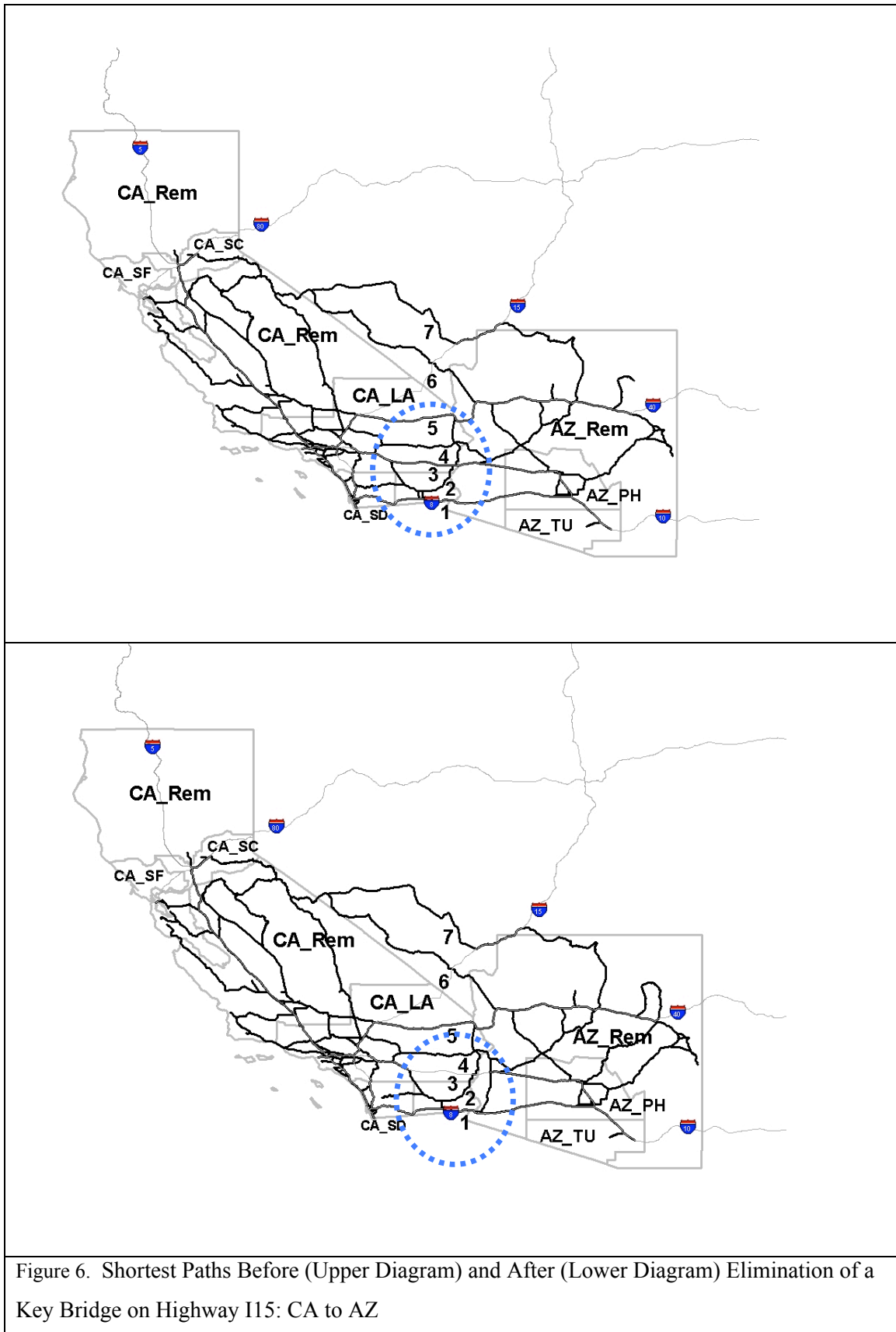


Table 3. Changes in the number of paths and dollar values of shipping on highways resulting from the elimination of major bridges: CA to NV

Route		0_2	0_1	1	2	3	4	5	6	7	8	9	10	11	12	Total	
Highway		S78	I40	I15	S190	S168	U6	S167	S182	U395	S88	U50	I80	S36	S299		
Baseline	# of paths	-	-	212	5	60	158	19	83	26	100	8	60	13	12	756	
	\$ value(A) ¹	-	-	7431	25	580	1837	210	811	256	1029	175	1105	194	151	13804	
Bridge Scenario	I80	# of paths	-	-	212	5	60	159	19	83	26	124	24	19	13	12	756
		\$ value(A ¹) ¹	-	-	7431	25	580	1846	210	811	256	1359	557	384	194	151	13804
		D=(A ¹) - (A) ¹	-	-	0	0	0	8	0	0	0	330	382	-721	0	0	0
		% change	-	-	0.0%	0.0%	0.0%	0.7%	0.0%	0.0%	0%	38.7%	182.6%	-60.1%	0%	0%	0%
	I15	# of paths	5	137	0	23	60	210	19	83	26	100	8	60	13	12	756
		\$ value(A ²) ¹	23	7031	0	114	580	2125	210	811	256	1029	175	1105	194	151	13804
		D=(A ²) - (A) ¹	-	-	-7431	89	0	287	0	0	0	0	0	0	0	0	0
		% change	-	-	-100.0%	360.0%	0.0%	15.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0%

Notes 1. Units: \$ Millions

2. Routes 0_1 and 0_2 are generated as alternatives to baseline shortest paths.

3. Entries for “# of paths” and “\$ value” are calculated for network crossing the State borders.

Table 4. Changes in the number of paths and dollar values of shipping on highways resulting from the elimination of major bridges: CA to AZ

		1	2	3	4	5	6	7	Total
Route									
Highway		I8	S78	I10	S62	I40	U95	S375	
# 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%	2,330.77%	12.15%	0%	0%	0%
Dollar Value ¹	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 1. Unit: \$ Millions

Table 5. 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 ¹
8	CA Los Angeles	5	AZ Phoenix	65	24,528	27,441	2,913	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	2,501	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	1,545	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	2,381	4.12%
12	CA remainder	6	AZ Tucson	76	55,203	56,414	1,211	2.19%
12	CA remainder	7	AZ remainder	228	151,493	151,815	322	0.21%
Total				1,134	695,714	710,567	14,853	2.13%

Note: 1. % change = (D / Before value) * 100

Table 6. California costs of purchasing truck mode services as a fraction of the total input value, 2001

USCsec.	Description	PTS ¹ (\$M.)	TIV ² (\$M.)	TCV ³
USC01	Live animals and live fish & Meat, fish, seafood, and their preparations	137.3	7892.6	0.0174
USC02	Cereal grains & 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 & Wood products	169.4	6675.9	0.0254
USC17	Pulp, newsprint, paper, and paperboard & 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
Total		5515.3	532356.0	0.0104

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).

- Notes
1. Purchase of truck services (\$M)
 2. Total input unit value (\$M.)
 3. Truck cost per unit value

Table 7. Shipping costs: California to Arizona

USC Sector	Description	Baseline			Scenario		
		Value of Shipping (\$M) ①	Avg. truck cost per mile ¹ (\$/Mile)	Total shipping cost (\$M) ②	Total shipping cost (\$M) ③	ΔCOST (\$M) ④=③-②	% Change ² ④/①
USC01	Live animals and live fish & Meat, fish, seafood, and their preparations	272.02	9.63	4.73	5.15	0.4139	0.15%
USC02	Cereal grains & 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 & Wood products	2298.11	113.88	58.37	63.03	4.6576	0.20%
USC17	Pulp, newsprint, paper, and paperboard & 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%

Notes 1. 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.

2. % change = (Δ cost / Shipping value) * 100.

Table 8. 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 & Meat, fish, seafood, and their preparations	0.414	0.519	0.825
USC02	Cereal grains & 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 & Wood products	4.658	5.031	7.775
USC17	Pulp, newsprint, paper, and paperboard & 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

Table 9. 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
VM	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

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