Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 732

Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System

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FOREWORD

By William C. Rogers
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NCHRP Report 732 describes the impacts of bottlenecks and interruptions to the flow of goods through the nation's major freight corridors and intermodal connectors, the dynamics of that flow in response to disruptions, and the full economic impact on public and private entities beyond just the critical infrastructure and the carriers that depend on that flow. The report developed two approaches to analyzing the economic impacts: (1) a high-level methodology (that provides the user with "rules of thumb" that can be used to estimate the likely economic costs associated with any type of disruption) based on the concept that the economic impact of any disruption would depend primarily on the commodity characteristics, the extent and nature of the disruption, and the costs associated with different elements of the cost structure; and (2) a more detailed methodology that depends on a much higher level of detail and more sophisticated analysis of the supply chain dynamic. This research will help to increase public understanding of the freight transportation system and improve the nation's ability to rapidly reconfigure the goods movement system to minimize disruptions.

The goods movement system in the United States has suffered from many large-scale disruptions since 2000. Examples include disruptions resulting from the terrorist events of September 11, 2001; the Baltimore rail tunnel fire in 2001; the lockout of dock labor unions at the Ports of Los Angeles and Long Beach in 2002; infrastructure failures after Hurricane Katrina in 2005; and the Midwest floods in 2008. Over this same period, new supply chain management techniques have created demands for highly efficient delivery systems. When disruptions to the system occur, especially to critical components, they can cause significant economic damage locally, regionally, and nationally. Unfortunately, the complex interrelationship between the goods movement system and economic activity is not well understood.

Under NCHRP Project 20-59(34), Georgia Tech, with the assistance of Parsons Brinckerhoff and A. Strauss-Wieder, was asked to develop and apply one or more conceptual methodologies for identifying and estimating economic impacts, both short and long term, due to disruptions to the goods movement system. To accomplish the research objective, the research team (1) reviewed and evaluated methodologies that have been used to measure direct and indirect economic impacts of disruptions to the goods movement system from natural and human causes; (2) considering a loss of capacity to the goods movement system lasting longer than 7 days and up to 1 year in duration, developed both a high-level and an in-depth methodology to estimate direct and indirect economic impacts over time and geographic scope; and (3) applied the proposed high-level methodology by estimating economic impacts in six case studies that assessed the results in terms of reliability and effectiveness and identified additional data needed for the application of the in-depth methodology in each of the case studies.

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Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SUMMARY

Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System

The relationship between a healthy economy and transportation system performance is one of the most important relationships in transportation policy. As long as commodities and goods need to move as part of the supply chain, providing reliable and cost-effective transportation capability is embedded in the supportive nature of transportation to economic productivity. When such capability is disrupted, either by man-made or natural means, economic losses—to the companies and individuals dependent on the supply chain as well to the broader society—could be significant.

Examples of such disruptions have occurred in the United States over the past several decades, including numerous hurricanes, major labor strikes such as the one affecting the West Coast ports in 2002, the closure of northern rail lines during the winter of 2006 for almost 2 weeks due to snow, the 2008 fuel price spike, freezing temperatures and flooding, the shutdown of the national aviation system during 9/11, and stoppages on critical transportation links such as the Baltimore rail tunnel fire. Internationally, disruptions in supply chains have also been caused by health concerns, such as the avian flu.

This report presents the findings of research completed for NCHRP Project 20-59(34), "Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System." The research had the following three objectives:

1. Synthesize the current state of knowledge of the economic impact of transportation disruptions on goods movement and relate this to a conceptual framework that describes key relationships,
2. Develop conceptual methodologies for estimating such economic impacts for different geographic and temporal scales, and
3. Illustrate the use of these methodologies at different scales and in different contexts.

A number of important issues for economic impact modeling surfaced from the literature review conducted for this research, as follows:

- The spatial or geographic scale of disruption will likely have a direct bearing on the magnitude and incidence of the economic impact. For example, the closing of a major port or key links in a land transportation network could have negative impacts throughout the supply chain, assuming little resiliency in moving goods on alternate paths. From a national perspective, however, the economic impacts might be very local (assuming that shippers and carriers can adjust the transportation component of the supply chain to serve the final consumers and still provide national benefits). Thus, the "perspective"—who is being impacted—will often produce different answers depending on context.
- A disruption could affect the entire freight system of an area or affect a specific mode. In the situation where a single mode is disrupted, shipments are likely to transfer to

alternative modes. The question then becomes whether the alternative modes have the capacity to handle the shipments and have the required approvals to transport such an unexpected demand in a timely and cost-effective manner.

- The temporal nature of disruption will also have potentially important economic consequences. A short disruption, that is, one lasting a day or up to a week, might cause some temporary or short-term economic loss, but overall would have minimal economic impacts. However, one lasting a much longer time could have severe consequences, depending on how industries and supply chains adjust. It should be noted that temporally short disruptions could also have long-term effects. Thus, network resiliency in placing back into service the necessary facilities and services to move cargo once more becomes an important consideration in assessing overall economic impact.
- The longer, more geographically extensive, and numerous breaks in the supply chain, the more extensive are likely to be the economic impacts. Shorter and less widespread disruptions, covering fewer supply chain/transport links are likely to entail limited economic impacts, primarily increased transport and inventory costs. Much more extensive and longer lasting disruptions will likely begin to effect productive economic activities, such as product assembly and manufacturing, or product distribution. When this occurs, regional and even national economic productivity and output can be reduced, affecting measurable economic performance such as gross domestic product (GDP). Firms may be able to "catch up" on production and demand may respond, but some net losses are likely even over time.
- The economic impact of severe bottlenecks and disruptions could affect a wide range of supply chain participants, not just the ocean carriers, truckers, railroads, and shippers that are using the network to transport the goods. These participants include public agencies, local labor unions, local retailers, warehousing and distribution providers, and—potentially—a significant number of consumers and economic organizations throughout the nation.
- Different types of disruption could have a range of direct and indirect economic impacts. For example, the removal of one critical link in a network could create a bottleneck that might or might not have important consequences to goods flow. On the other hand, widespread network disruption (for example, due to floods and hurricanes) could have a multitude of overlapping and connected economic impacts.
- Whether goods can be shipped economically via other modes depends, in addition to the availability of service, on the value and nature of the cargo itself. High-value commodities or commodities that are otherwise time sensitive, such as air cargo, may not economically be shifted to slower modes.
- Network resiliency (through either redundancy or business flexibility) is a very important characteristic of economic impact. If, for example, goods flowing through a particular bottleneck can be rerouted without significant economic costs, the overall economic impact of a bottleneck could be minimal, ignoring for a moment the economic consequences to the local economy.
- Assessing economic effects has to take into account the nature of the methodologies being used and the questions being asked. For example, a disruption that shifts shipments from rail to truck may require that far more truck drivers be used. Some economic models would see this as a positive impact offsetting losses to other modes and sectors—more workers are being employed. However, from a user perspective, the system has become potentially less efficient and not enough drivers and/or highway capacity may exist to handle the increased shipments. Accordingly, the analysis of disruptions may require more of a "toolkit," rather than a "one-size fits all" model, organized within a consistent methodological framework.
- The global goods movement supply chain is a multi-tiered system with various entities, stakeholders, networks, and modes involved, that spans a huge physical space, and by its

very nature is susceptible to natural and human-caused disruptions. International supply chains are also intricately interconnected.

- In case of a major event, such as a terrorist attack or an earthquake, standard risk mitigation measures, such as increasing safety stock, diversifying supply base, and building redundancy into logistical systems, may or may not afford much protection from damage. At the same time, the probability of occurrence of such events is small.
- Disruption resistance (security) and tolerance (resilience or recovery) are both important measures in disruption management. These measures have to be balanced with concerns regarding productivity while promising to provide sufficient benefits to justify costs. These measures could include increased electronic surveillance, such as in the case of global container movement, or having back-up suppliers, as in the case of a business that procures raw material, so that if a disruption event affects one supplier, there is a fallback. The assumptions regarding resistance and resilience are important in understanding estimates of disruption impacts.
- Various types of economic models can help estimate the potential for losses due to a disruption in the supply chain. These range from simple logical frameworks to complicated dynamic economic simulations. However, it is important to understand the underlying assumptions of these models, particularly with regard to resiliency of, and interdependencies among, businesses and infrastructures. The order of magnitude of loss estimation can be largely affected by these assumptions.

A sequential five-step process was developed as a comprehensive and practicable framework for evaluating a wide range of freight network disruption events and their many possible economic impacts. The initial step **identifies the direct and immediate physical effects of a network disruption,** including the identification of the specific transportation facilities affected and the associated modes of transport within, into, and out of the region impacted.

The second step **identifies current and future affected network flows by facility and link.** A variety of more or less severe impacts on day-to-day operations are possible, from a rerouting of local or through traffic or a reassignment of vessels to other berths or terminals, to shifts in operating times to avoid increased on-network congestion. Longer term disruptions involving major damage to port or other terminal facilities may lead to truck, train, vessel, or aircraft rerouting to other locations and to a resulting drop in local freight traffic volumes.

The third step **identifies supply chain characteristics and parameters.** Freight supply chains, which involve moving a commodity from production site to final customers, differ a good deal by commodity transported, including whether the cargo involves shipping raw materials, intermediate, or finished goods. Both physical and financial/institutional adjustments will often be required, typically leading to higher total transaction costs.

The fourth step **models the response of the supply chain to disruptions,** the most challenging of the five steps in the process. Possible models might focus in the short term on rail, barge, truck, and air freight traffic rerouting, including the possible rerouting of transcontinental landed trade or ocean vessel movements; mode shifts; source-market restructuring of origin-destination flows and more permanent restructuring of origin-destination flows; and industry responses, including inventory draw-downs, reduced or suspended production levels, and shifts in the location(s) of production.

The final step **models the economic impacts of network disruptions.** The extent and depth of economic impact modeling will depend heavily on what is assumed about supply chain responses to disruptions, or what is estimated based on more in-depth modeling.

Modeling should examine the following types of costs.

Social and Public Sector Costs

- Changes (increases or decreases) in network maintenance costs, based on net regional, mode-specific vehicle miles of travel (VMT) changes
  - Changes from traffic rerouting will have little impact on overall routine highway maintenance costs, since regional VMT will not change much, but there can be a transfer of impacts from one location—or possibly from one state—to another—in cases of widespread diversion incidence.
  - Changes are more significant where modal diversions occur and truck volumes fall significantly across the entire network.
- Increased network congestion on undamaged facilities
  - Crude estimates can be based on additional VMT under congested conditions and based on diversion assumptions or actual diversion analysis.
  - Within a travel demand model itself, additional levels of link congestion can be estimated and measured using metrics such as VMT or vehicle hours of travel (VHT) under congested conditions (levels of service [LOS] D,E,F).
- Changes in externalities, such as emissions, based on net regional changes in mode-specific vehicle miles of travel
  - These impacts may also need to be weighted to reflect increased overall levels of congestion from truck reroutings, i.e., if volumes are diverted from LOS C facilities to other facilities, which then operate under LOS F, emissions and congestion costs would both experience net increases.

Direct Supply Chain Costs

- Increased direct truck transport costs from diversion, based on VMT and VHT changes.
  - Given truck VMT and VHT changes, trucking cost factors can be readily obtained from numerous benefit-cost analysis studies and sources.
- Increased inventory carrying costs, calculated based on changes in ton hours by commodity type, value of the commodity, and assumed time value of money (inventory costs)
  - Increased direct truck transport costs from diversion can lead to increased inventory costs, calculated based on changes in ton hours by commodity type, value of the commodity, and assumed time value of money (inventory costs).

Assumptions may also need to be made about the share of shipper costs borne by/passed on to the carrier, or to beneficial cargo owners (BCOs). Assessments should also reflect net regional impacts, such as potential increases in local trucking activity in some areas at the expense of other areas, i.e., potentially no net change in costs or benefits, but a change in the spatial distribution of impacts. Measures include producer and consumer surplus.

Based on the relevant literature, case studies, and the research team's experience in freight, logistics, and economic impact analysis, it was determined that a general methodology could be developed that grouped impacts according to common characteristics and that simplified the analysis in such a way that a high proportion of the economic effects could be readily captured. This so-called high-level methodology uses "rules of thumb" for estimating the economic costs associated with different components of a system disruption. The economic impact of any particular disruption would depend primarily on the commodity characteristics, the characteristics of the disruption, and the costs associated with different elements of the cost structure (e.g., transport/logistics costs, inventory costs, and productivity and output losses) (see Figure S-1).

It is apparent that a high-level methodology, while involving simplification, is not necessarily "simplistic." Rather, the methodology must reflect important distinctions across

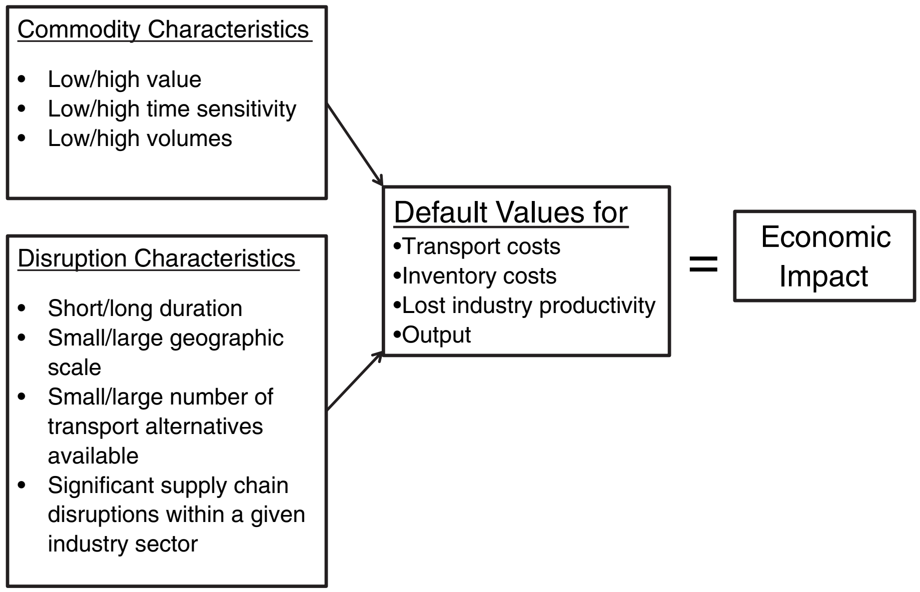


Figure S-1. Basic concepts in a high-level economic impact methodology.

a number of key variables, which would determine economic outcomes, and also dictate analytic methods. The high-level methodology is intended to capture the most likely general set of supply chain and economic impact outcomes. The more detailed methodology depends on a much higher level of detail and more sophisticated analysis of the supply chain dynamic (especially under stress). To fully implement the more detailed methodology, further research would have to be conducted on several elements of the analysis approach, especially the supply chain response to external forces.

CHAPTER 1

Introduction and Background

1.1 Background

The relationship between a healthy economy and transportation system performance is one of the most important relationships in transportation policy (see, for example, Washington State DOT, 2011). As long as commodities and goods need to move as part of the supply chain, providing reliable and cost-effective transportation capability is embedded in the supportive nature of transportation to economic productivity. When such capability is disrupted, either by man-made or natural means, economic losses—to the companies and individuals dependent on the supply chain as well to the broader society—could be significant.

Examples of such disruptions have occurred in the United States over the past several decades, including numerous hurricanes, major labor strikes such as the one affecting the West Coast ports in 2002, the closure of northern rail lines during the winter of 2006 for almost 2 weeks due to snow, the 2008 fuel price spike, freezing temperatures and flooding, the shutdown of the national aviation system during 9/11, and stoppages on critical transportation links such as the Baltimore rail tunnel fire. Internationally, disruptions in supply chains have also been caused by health concerns, such as the avian flu.

Disruptions such as these not only affect society at large in terms of economic losses and possible environmental impacts from the diverted movements, but so too they can affect the carriers and shippers that provide the services. For example, severe flooding in Arizona and Southern California in 2006 caused an international container carrier to divert two of its mega vessels from the ports of Los Angeles/Long Beach to the Port of Tacoma. Approximately 15,000 containers now had to be unloaded at Tacoma. Two major issues, however, caused this seemingly rational business decision to become very complex very quickly. Customs and Border Protection (CPB) in Los Angeles refused to release the cargo to the CPB office in Seattle and a major railroad serving the Port of Tacoma was informed late in the process of the arrival of the containers, resulting in inadequate rail assets being available to move the containers. As a result, the carrier had to take 7,000 containers back to Los Angeles, causing significant delay and disruption to the supply chain for the cargo carried on the ship and additional costs to the carrier.

This report presents the findings of research completed for NCHRP Project 20-59(34), "Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System." The research examined many different dimensions of disruptions. For example, one of the key issues relating to transportation system disruptions is the magnitude and reach of economic impact(s) that will be associated with such events. Although knowing what these impacts might be is a critical consideration in determining appropriate mitigation and response strategies, many uncertainties hinder a full understanding of the scope and nature of such economic consequences. Understanding the relationships among goods movement/supply chain participants, governmental policies, regulations, and economic activity, especially in the context of disruptions, is complex.

And yet much of public policy oriented to responding to (or anticipating) such disruptions in a way that minimizes economic costs requires a basic familiarity with these integrated relationships. Analyzing the economic effects of such situations can help inform institutional and policy decisions and lead to better responses, thus enhancing the resiliency and efficiency of the overall system.

1.2 Research Objectives

The goal of this research was to develop and apply one or more conceptual methodologies for identifying and estimating the short- and long-term impacts of disruptions to the goods movement system. In order to accomplish this goal, the research had the following three objectives:

1. Synthesize the current state of knowledge of the economic impact of transportation disruptions on goods movement and relate this to a conceptual framework that describes key relationships,
2. Develop conceptual methodologies for estimating such economic impacts for different geographic and temporal scales, and
3. Illustrate the use of these methodologies at different scales and in different contexts.

1.3 Research Approach

Figure 1-1 shows, as a high-level concept, how to conduct an analysis of the impacts of transportation system disruptions. This structure has been used as a successful foundation in other projects that have examined such impacts. The focus of this research project is in Step 2, the development of both a high-level (i.e., use of rules of thumb for estimating economic impacts) and a more in-depth analysis methodology (i.e., more detailed analysis) for estimating the economic impacts of system disruptions. One of the important concepts in developing such methodologies is to construct a tool kit of approaches that can be used for different types of disruptions and impacts.

The research approach consisted of the following six tasks.

Task 1: Develop a conceptual framework that illustrates the relationship between the supply chain, network performance (and disruptions), governmental policies, and economic impacts.

This research began by developing a conceptual framework for understanding the relationships among network performance, supply chain practices, and government policies, and how

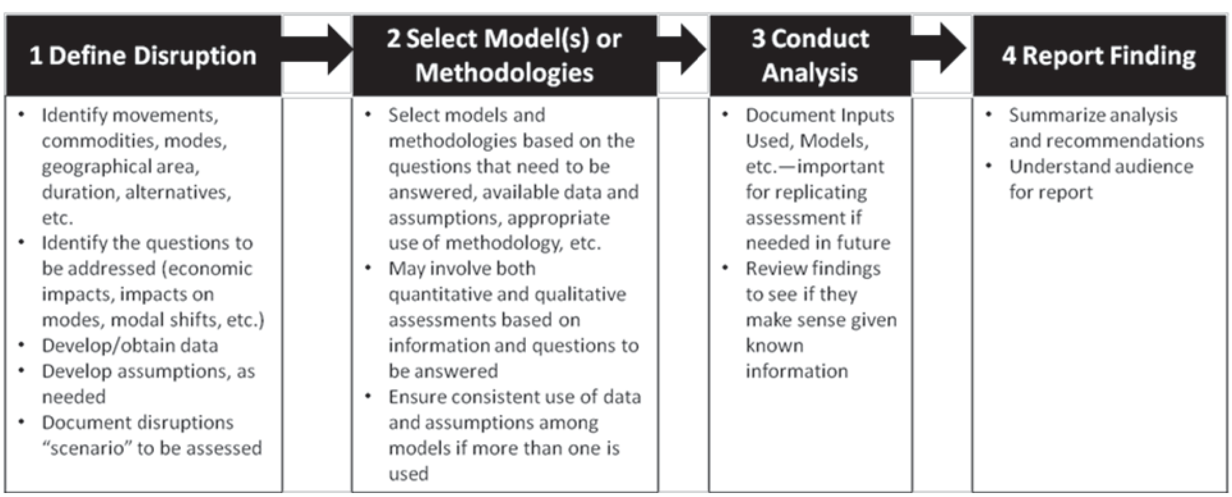


Figure 1-1. Conceptual foundation for conducting disruption-related impact analyses.

these affect economic impacts when disruptions in the transportation system occur. A major goal of this research was to develop interest among transportation officials in using the methodologies developed as part of this project. Such a goal, in turn, required a well thought out description of the relationships among the different variables that could influence economic impacts resulting from a disruption.

As noted earlier, many different aspects of these relationships add to the complexity of such an understanding. The purpose of a conceptual framework is to identify the key variables that will influence the magnitude and direction of a particular outcome. For example, a study by North Carolina State University's Supply Chain Resource Cooperative identified a long list of variables that would increase the impact of disruptions in the supply chain, including such items as customs regulations, storage requirements, security requirements, and legislative actions related to importing or global sourcing. The study identified the following variables as particularly influential in determining the impacts of unexpected and abrupt disruptions: number of transfer points (for diverted traffic), vessel capacity and channel overload, port issues and infrastructure, land transportation network capacities, potential for terrorism, and natural disasters.

The conceptual framework needs to include different elements of a typical supply chain and the dependence of economic productivity on a functioning transportation system (and of the different components of this system, such as ports, intermodal terminals, roads, etc.). Several researchers have examined the impact on the supply chain and the different ways of conceptualizing the economic consequences of disruptions. Kleindorfer and Saad (2005), for example, identified different types of risks involved with supply chain disruptions and strategies that could be adopted to "manage" such risks. Similarly, Tomlin (2006) looked at the economic value of mitigation and contingency strategies for different types of risks along the supply chain. Wilson (2007) looked specifically at the impact of transportation disruptions on supply chain performance and, in the process, identified the "transportation sensitive" components of the supply chain and the consequences of disruptions.

This supply chain perspective is a critical component of an overall conceptual framework that examines the economic consequences of transportation system disruptions. However, the economic consequences of such disruptions will go beyond just the supply chain and potentially will include national, regional, state, and local economic impacts. Many of these impacts will be caused by supply chain disruptions (e.g., reduction in local labor income because of goods temporarily not moving through a bottleneck point).

Task 2: Review and evaluate methodologies to measure direct and indirect economic impacts of disruptions to the goods movement system.

A literature review was conducted to identify different methodologies that have been used in practice and that could serve as a base from which to choose the methodologies described in Task 3. The results of this literature review were combined with the research team's own experience and expertise in economic modeling to identify different types of methodologies that could be used to measure direct and indirect economic impacts.

Once a comprehensive list of economic impact methodologies had been identified, the methodologies were evaluated based on a set of criteria that directly related to the formulation and use of the methodologies being examined as part of this research project. Evaluation criteria were used that reflected the different characteristics that make a particular methodology appropriate for the assessment of particular disruption situations. The results of this literature review were combined with the research team's own experience and expertise in economic modeling to identify different approaches that could be used to measure direct and indirect economic impacts associated with disruptions. Each approach was then evaluated against a set of criteria deemed appropriate for the assessment of particular disruption situations. Here, the results of Task 1 fed into the understanding of the key relationships and the types of approaches one can use to analyze them. A detailed set of evaluation criteria related to such things as data requirements, model specification, timeframe for impact assessment, direct and indirect impact definitions, typical outputs, etc., was developed for this purpose. The methodologies that best reflected the requirements of both the high-level and more in-depth economic impact analyses, along with their ability to characterize a disruption, were identified and their characteristics and model forms used in Task 3.

Task 3: Develop both a high-level and an in-depth methodology for estimating the direct and indirect impacts of network disruptions.

Based on the results of Tasks 1 and 3, this task developed approaches for a high-level economic impact analysis methodology and one focusing at a much higher level of detail, referred to as an in-depth economic impact analysis methodology. In the initial stages of the research, the intent was to develop the high-level methodology, show its potential application, and then discuss how a more in-depth methodology could result. During the course of the research, however, it was found that identifying all of the possible components of a supply chain and how they could be modeled or analyzed in the context of a transportation system disruption was a more appropriate beginning for the research. By doing so, the research team was able to lay the foundation for both the in-depth methodology as well as the high-level approach. Thus, in this report, the more detailed analysis approach is presented first, followed by the high-level methodology.

It was important to note early on that the economic impacts of system disruptions will vary across several key attributes. Figure 1-2 illustrates the concept of how economic impacts could

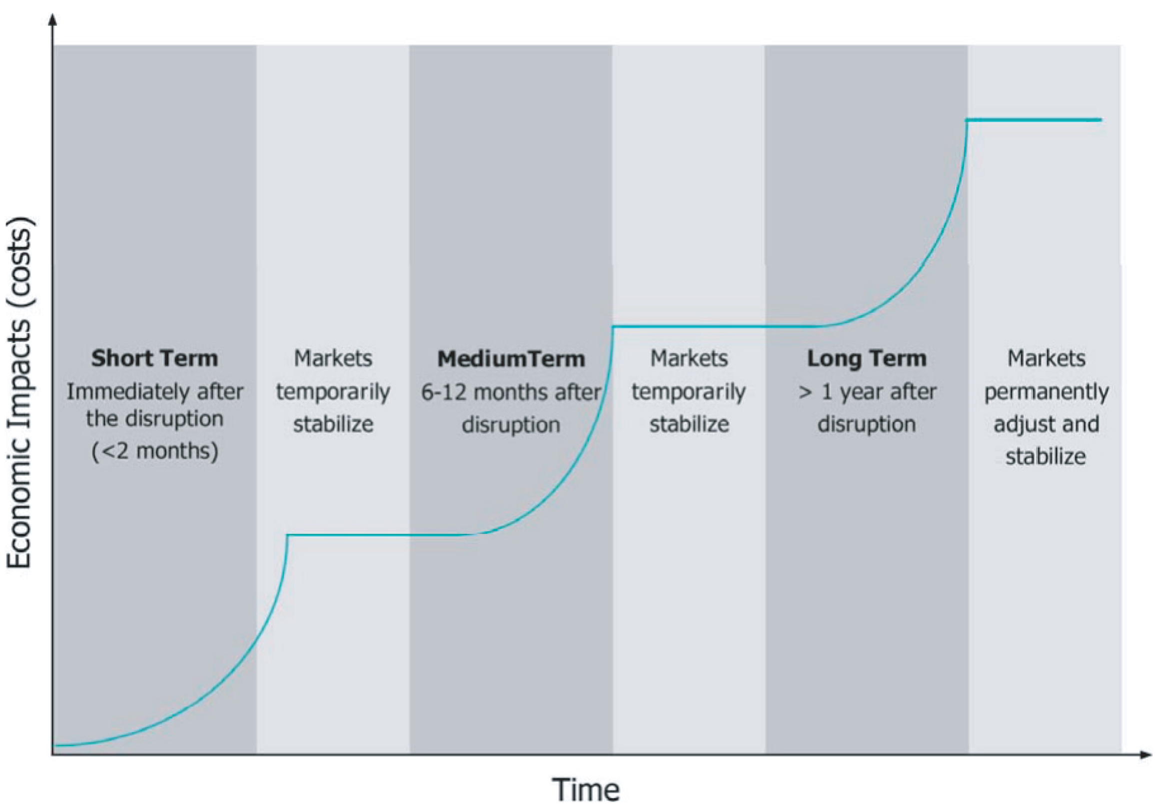


Figure 1-2. Variability of economic impacts over time.

vary over time. In this illustrative example, the disruption has a staged effect on regional economic costs.

- Stage 1—In the immediate aftermath of the disruption there would be a diversion of freight to other modes and routes, or in some cases, cargo would stop flowing. This would be a temporary diversion that would result in economic costs stabilizing after the initial shock (flat line).
- Stage 2—As disruption effects linger, production may fall and inventories are depleted, but freight-related businesses and other service industries will begin to adjust staff and inventories according to newly established demand levels. This second round of effects may also stabilize (flat line).
- Stage 3—Transportation/supply chain adjustments are fully implemented where possible (but at higher cost than before the disruption); some industries further adjust by shifting production to other locations where possible. Firms that cannot adjust supply chains or adjust their production locations may go out of business. After this permanent adjustment, the regional economy equilibrates at a different point.

Although the figure does indicate a range of time (e.g., <2 months, 6–12 months, >1 year), in reality, the amount of time that it will take for each market impact to occur will likely vary by the type and scale of disruption, the specific industry or groups of industries and types of commodities and the modes involved. Although the figure is consistent with many studies that indicate increasing costs over time, it is not necessarily the only pattern. For example, economic costs may actually be greatest on a national basis in the medium term, if long-run adjustments are not yet established, but inventories are drawn down and significant supply chain disruptions begin to occur. Over time, long-run logistics adjustments may actually mitigate the effects (e.g., by shifting production to other locations or by major supply chain adjustments), so that costs plateau or even decline some.

An analytic progression in problem solving should be followed for conducting economic analysis of system disruptions. This includes the following basic steps:

1. Compile as much freight flow data as possible across the affected network, within the time and resources available for study. Freight should be disaggregated by mode and by industry and commodity as much as possible.
2. Compute short-term direct effects based on an analysis of route and mode diversions. Direct effects are transportation and inventory costs from longer and slower routes and differences in modal costs (e.g., shifts from rail to truck, which are more costly on a per ton basis).
3. Other direct effects are added if a major transportation facility that employs numerous people shuts down or dramatically reduces activity, for example when vessels are not calling or containers cannot be moved.
4. Indirect economic effects for the short run can be estimated from the direct effects, using input-output (I-O) or other economic impact models.
5. For an in-depth methodology, that is, one that includes more variables and can be applied at a greater level of detail, more "behavioral" responses over the longer term (for disruptions that last a long time) may be added. These could include additional problems along the supply chain not reflected in the diversion analysis, or supply chain adjustments over time. Industry responses too can be added, mainly for long-term and very extensive disruptions, where industrial production goes to an off-shore plant or to a plant in another region and alternative supply chain practices are implemented. Behavior responses could be incorporated based on econometric models, dynamic simulation models, or by judgment-based adjustments to the results, each based on detailed industry supply chain data.

Different methodologies might be appropriate for different types of issues that are being examined, the level of detail being pursued (high level vs. in-depth methods), the types of available data, and the geographic scope of the impacts.

Task 4: Prepare an interim report and propose case studies for evaluation in Task 5.

An interim report was produced that summarized the results of Tasks 1, 2, and 3. In addition, potential case studies of transportation system disruptions were recommended for project panel consideration. These case studies included historical cases and reflected different modes, geographies, time periods, and ranges of impacts.

Task 5: Apply the high-level methodology and identify the additional data and steps needed to implement the in-depth economic impact methodology.

The high-level methodology was developed with actual application in mind. In other words, the types of data required, the complexity of the analysis, and the metrics that are reported were defined in a way that will be relevant to transportation officials. The high-level methodology was applied to a case study to show how it can be used to estimate, in general terms, the economic impacts of system disruptions. The application of the methodology focused on national, regional, and local economic impacts (to the extent that data were available) to examine impacts at each level. The application was validated against economic studies that had been conducted on the disruption itself to see how close the high-level methodology came to study results.

Task 6: Prepare a final report.

The final task was the preparation of this report.

1.4 Intended Audience

This research is aimed at providing information to four primary audiences. The first is the public official who is often involved in developing or making the decisions regarding transportation systems and networks that will be effective in a wide range of operational scenarios. Understanding the economic implications of system disruptions will be an important point of departure for establishing resilient networks and response strategies that could minimize economic consequences. This audience needs to know the importance of the tradeoffs among the many different objectives that can be considered with respect to network resiliency and system structure.

The second audience is the general public that needs to gain a better perspective on the relationship between economic productivity and transportation system performance. Economic impact assessments can translate transportation disruptions into terms more readily understandable by the general public, including the numbers of jobs affected.

The third audience for this research is the educational community. To some extent, the first two audiences above represent the current professional and decision-making community, with all of the challenges of dealing with the transportation system operations that they represent. The research team thought that an important audience for this research must be the universities and colleges that will be producing tomorrow's transportation professionals, and thus the materials developed by this project should be viewed as potential inputs into course curricula and as background for further research. This project will also help to define where more research and new/improved models are needed, which is work often undertaken by universities.

The fourth, and in some minds, the most important audience is the "end-user" community of shippers, transportation carriers, terminal operators and logistics providers. This community is the most impacted by the decisions, policies, and plans made by those entities that do not have a commercial stake, but are relied upon to provide the necessary services and infrastructure during disruptions. Thus, this community must not only understand the current and proposed implications identified in this study, but also be allowed to provide meaningful comment on how these implications and findings will impact the reality of goods movement within their purview.

1.5 Report Organization

The remainder of this report is organized in the following manner:

- Chapter 2 presents a literature review of economic impact analysis models that have been used in disruption studies.
- Chapter 3 presents a detailed analysis framework that can be used to do an in-depth economic analysis of transportation system disruption. Note that the more in-depth analysis framework is presented first simply because it was more logical to understand fully the different variables and relationships that constitute a valid analysis framework before thinking about a more general, high-level method.
- Chapter 4 presents case studies of transportation system disruptions that have occurred over the past 15 years in the United States. These case studies were an important foundation for identifying the rules of thumb for economic impact analysis that constituted the high-level methodology.
- Chapter 5 describes the high-level methodology and the rules of thumb that can be used for estimating economic impacts. The methodology is applied against a real disruption case study and the results compared.
- Chapter 6 presents conclusions and identifies future areas of research.

CHAPTER 2

Methodologies to Measure Direct and Indirect Economic Impacts of Disruptions to the Goods Movement System

2.1 Overview

This chapter reviews the literature that covers both the fundamental concepts associated with, and the methods of assessing, economic impacts of supply chain disruptions. A general framework reflecting a hierarchy of possible approaches that are progressively more complex is used to organize the literature review. As shown in Table 2-1, there are two broad classes of tools that can be used to model economic impacts of a transportation network disruption—*supply chain response models* and *economic impact models.* These may be regarded as sequentially linked. First, supply chain response models consider the impact of a disruption on supply chains (e.g., is cargo diverted to another route? is it held back for a time? does sourcing adjust?). Following this, and based on how supply chains are thought to adjust, economic impact methodologies help to assess the impact of the disruption on the economy. The economic modeling component essentially asks: if the supply chain adjusts in a certain way, what are the economic losses associated with these adjustments? This may involve estimating the sum total of impacts on businesses, jobs, households, and people of a disruption at various scales, including local, regional, national, and even international levels.

2.1.1 Supply Chain Response Models

There are several common approaches or categories of supply chain response models described in the literature. These include

- Network-based models
  - Simple cargo diversion models that are often based on a least-cost path algorithm of varying degrees of complexity
  - Freight network simulation models
- Industry supply chain response models
  - Business supply chain optimization models
  - Dynamic supply chain simulation models

Network-Based Models

Simple Cargo Diversion Models: Diversion models are often quite simple and can be based on the assumption that, in the case of a transportation network disruption, cargo is diverted to the least-cost alternative route. This diversion leads to some direct impacts in terms of increased transportation costs (e.g., fuel, operator salaries, operations and maintenance, etc.) and certain indirect impacts (such as increased inventory costs imposed by the relative uncertainty of deliveries through the detour, lost shipper profit, etc.). The sum total of these costs can be

Table 2-1. Classification of available disruption impact assessment methodologies.

	Network-Based Models	Industry Supply Chain Models
SUPPLY CHAIN RESPONSE MODELS	Assume freight is diverted and estimate transport cost and inventory value impacts. Includes: -Simple Cargo Diversion Models -Freight Network Simulation Models	Are used to optimize business operations and address industry choices/decisions regarding sourcing, inventory levels, and route choice. Includes: -Business Supply Chain Optimization Models -Dynamic Supply Chain Simulation Models
ECONOMIC IMPACT METHODOLOGIES	Static/Input-Output-Based Models	Dynamic Economic Simulation Models
	Assume declines in industry final demand and calculate direct, indirect, and induced impacts across all industries	Assume changes in supply, demand, output, prices, or other direct economic impacts, and simulates overall economic impact via dynamic modeling

Increasing Levels of Complexity →

considered the immediate, or first order, economic impact of the disruption. Inter-industry linkages or residual economic and societal dislocations may or may not be considered in these models, depending on the economic impact tool used.

These models tend to take a short-term view of disruption impacts. They are relatively less complex and less data or skill intensive and hence can be easier to use than full supply chain modeling tools. An example of this type of model includes the Freidman et al. (2006) Disruption Impact Estimating Tool-Transportation (DIETT) Model.

Although diversion models tend to be simple when employed at a large scale of analysis, they can be complex when applied to specific transportation facilities. For example, a number of very detailed port disruption models simulate potential operational (and even policy) responses to disruptions to the port itself, or to port intermodal connections. These models tend to be operational simulations of greater or lesser complexity. Examples include IOCG's Maritime Security Risk Analysis Model (MSRAM), which is capable of performing scenario analysis as well as assessing the impacts of a disruption event.

Several studies were found in the literature where no formal or rigorous attempt was made to actually model diversions based on cost parameters, but rather assumptions were put forth about what might happen to goods movement in the face of a disruption, and these were tested as alternative cases. See, for example, Arnold et al. (2006).

Freight Network Simulation Models: These models are complicated versions of simple diversion models. Generally GIS-based platforms that replicate the complex network of routes through which freight flows occur, they either represent movement on a single mode (such as trucks over the road network) or over multiple modes. As with the simple cargo diversion models, a least-cost (including time cost) or shortest route approach is applied to analyze freight flows in various scenarios. The models usually have the ability to analyze scenarios in which certain links or nodes in a network are rendered dysfunctional.

Examples of this type of modeling tool include the Oak Ridge National Laboratory's (ORNL's) Transportation Routing Analysis Geographic System (TRAGIS), which has the ability to conduct both single-route and multiple-route analysis. Other commercially available network simulation models such as those included in the TransCAD GIS-based modeling software and VISUM also fall in this category of model.

Industry Supply Chain Models

Business Supply Chain Optimization Models: These models aim at optimizing business operations including the flow of goods (raw materials, intermediate and finished products) through a specific industry supply chain. Business and industry decisions regarding sourcing, inventory levels, and the transportation network or route choice form key components of the supply chain and are all vulnerable to impacts of major disruptions. These models help to re-examine key business decisions as the business situation changes. Port disruption models such as the Port Disruption Recovery Model (PDRM) are an example of this category of models. Wilson (2007), Lewis et al. (2006), and Dauelsberg and Outkin (2005) have demonstrated applications of these models to hypothetical cases of supply chain disruption.

Dynamic Supply Chain Simulation Models: These models aim to capture supply chain responses dynamically and allow for ongoing assessment of raw material sources, factory locations and processes, distribution centers, transportation links, outsourcing, inventory and related costs, and constraints. These new modeling tools can be categorized as complete dynamic supply chain models. Some of these models are highly complex formulations that simulate supply chain networks spatially as well as temporally. Nagurney et al. (2002), for example, modeled the physical, information, and financial networks involved in commodity markets. These models are generally very demanding in terms of data requirements and skill levels of the modelers and are as yet in the early stages of development as far as their use in common practice.

2.1.2 Economic Impact Models

Economic impact models can be classified into the following two broad categories:

- Static/Input-Output (I-O) Models
- Dynamic Economic Simulation Models

Static/Input-Output Models

These are models of varying complexity that focus on transport costs (the monetary value of time and other resource costs). The most widely used tools are I-O modeling tools. Within the context of disruption modeling, I-O modeling tools can be applied primarily to analyze the following two situations:

- Economic damages to freight transportation infrastructure—These models focus on the costs to transportation facilities themselves and the damages incurred and can also include the economic costs of mitigation (supply chain disruption response measures) going into the future. A good example of such a model is the MARAD Port Economic Impact Kit, which focuses on the costs incurred directly within a port (e.g., when dock workers are laid off), and the spinoff impacts to industries and enterprises that supply goods and services to the port.
- Economic damages associated with supply chain disruptions and cargo diversions or bottlenecks that disrupt freight flows.

I-O models capture the inter-industry linkages of a disruption event on a regional economy by using matrices that relate the outputs of one industry to inputs of all other industries. That is, the goods and services demanded by one industry constructed as inputs in the form of goods and services provided by other industries. Multipliers (employment, output, earnings, and value added), which are derived from these inter-industry linkages, are the key input into estimating long-term economic growth and development. Standard economic multipliers produced by input-output models estimate both direct impacts and two kinds of secondary impacts resulting from these direct changes to an economy—indirect impacts and induced impacts. Direct changes to an economy usually are represented by employment, sales, or purchases (spending), which would result from an increase/decrease in final demand for a given industry sector or for households. Indirect impacts, sometimes referred to as backward linkages, result from the intermediate purchases necessary to operate a business. To the extent that local firms buy more/less from local suppliers, the indirect impact will be larger/smaller. Induced effects, sometimes referred to as forward linkages, stem from the re-spending of household earnings by workers who benefit from direct and indirect activity. In other words, if a new firm is attracted to the local area, the employees of that firm will spend some proportion of their earnings at local shops, restaurants, etc. Ham et al. (2005), for example, demonstrates the estimation of interregional impacts of major transportation disruptions using such an I-O approach.

I-O models may be especially effective when there is a zonal-based freight network flow or travel demand model that can capture the change in freight flows on the network due to a disruption. In the absence of such a demand model there are "short cut" methods that can be used to simulate the disruption's effect on freight flows.

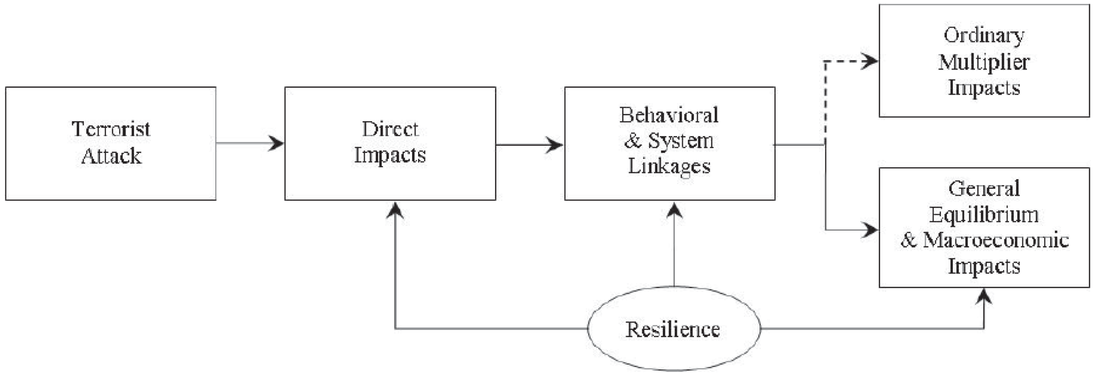
Dynamic Economic Simulation Models

These models are statistically estimated, simultaneous equation representations of the aggregate workings of an economy. They have forecasting capabilities that can be helpful in determining the potential impacts of a future event or in distinguishing the actual activity of an economy from what it would have been like in the absence of a shock. Econometric models have their own established set of criteria for model validation that are more rigorous than those for I-O models. Uncertainty is inherently incorporated in the models by virtue of their stochastic estimation. The downside of these models is their high level of complexity and user skill requirement. If available as off-the-shelf software, most aspects of the model, underlying assumptions as well as equations, are generally opaque to the user. Furthermore, these models require historical time series data and tend to be data intensive. Examples of dynamic simulation modeling tools that have been (or could be used) for disruption analysis include the Regional Economic Model Inc. (REMI) and University of Maryland's Long-term Inter-industry Forecasting Tool (LIFT). Studies that have utilized this approach include Rose et al. (2007), Tsuchiya et al. (2007), and Arnold et al. (2006).

2.2 Research on Economic Impacts of Disruptions to the Goods Movement System

This section reviews papers on the economic analysis of supply chain disruptions, primarily viewed from a conceptual perspective. The research represented in these papers provides some key concepts regarding supply chain disruptions that helped form the theoretical basis for the development of an impact assessment methodology.

Rose (2009) presents a schematic framework for assessing direct impacts (such as property damage, site-specific business disruption) and extended impacts (supply chain interdependencies among different types of infrastructure) of major disruptions such as a terrorist attack (see Figure 2-1). The framework can be used for identifying and classifying direct, microeconomic, and macroeconomic impacts to form a basis for disaster loss estimation. The paper emphasizes the concept of resilience, broken down into micro resilience (i.e., substitution, conservation, rescheduling) and macro resilience (i.e., price system and market strengthening). The paper also contends that behavioral linkages (e.g., fear of flying after an event like 9/11) or social amplification of risk is a major driver of the long-term impacts of disaster-occasioned disruptions that are not often quantified when estimating the economic impacts of such events.



Source: Rose (2009).

Figure 2-1. Framework for assessing direct and extended impacts of disruptions.

The paper proposes an operational measure of direct economic resilience (DER), defined as the extent to which the estimated direct output reduction deviates from the likely maximum potential reduction given an external shock.

Although there are several economic models that are used to estimate economic impacts of disruptions (such as I-O, computable general equilibrium, macro-econometric models), Rose contends that these estimates will likely not vary by more than 50 percent between methods. Resilience and behavioral linkages can, however, result in 10-fold differences in loss estimates. Benefit-cost analysis (by governments and businesses alike) should be broadened to also consider both mitigation (pre-event) and resilience (post-event) options.

TranSystems (2008) proposes a framework to develop a tool to analyze potential transportation security incidents (TSI) and the resulting effects. The tool aims to address the interdependencies among port, terminal, vessel, rail line, and local and regional cargo flows. The tool provides a method of assessing service impacts (capacity, cost, time, etc.) through an operatIonal framework that dynamically mimics multiple freight flows across and through various diverted transportation modes, corridors, and facilities.

Chopra et al. (2007) demonstrated the importance of decoupling recurrent supply risk and disruption supply risk. In terms of supply chains, disruptions are defined as interruption of supply due to an unforeseen circumstance, whereas recurrent supply risks are delays resulting from inherent (in the supply chain) or recurrent uncertainties. This classification of risk as recurrent or disruption risk can help inform the decision regarding an appropriate supplier. Bundling together two types of uncertainties would potentially underutilize a reliable source while over-utilizing a cheaper, but less-reliable source.

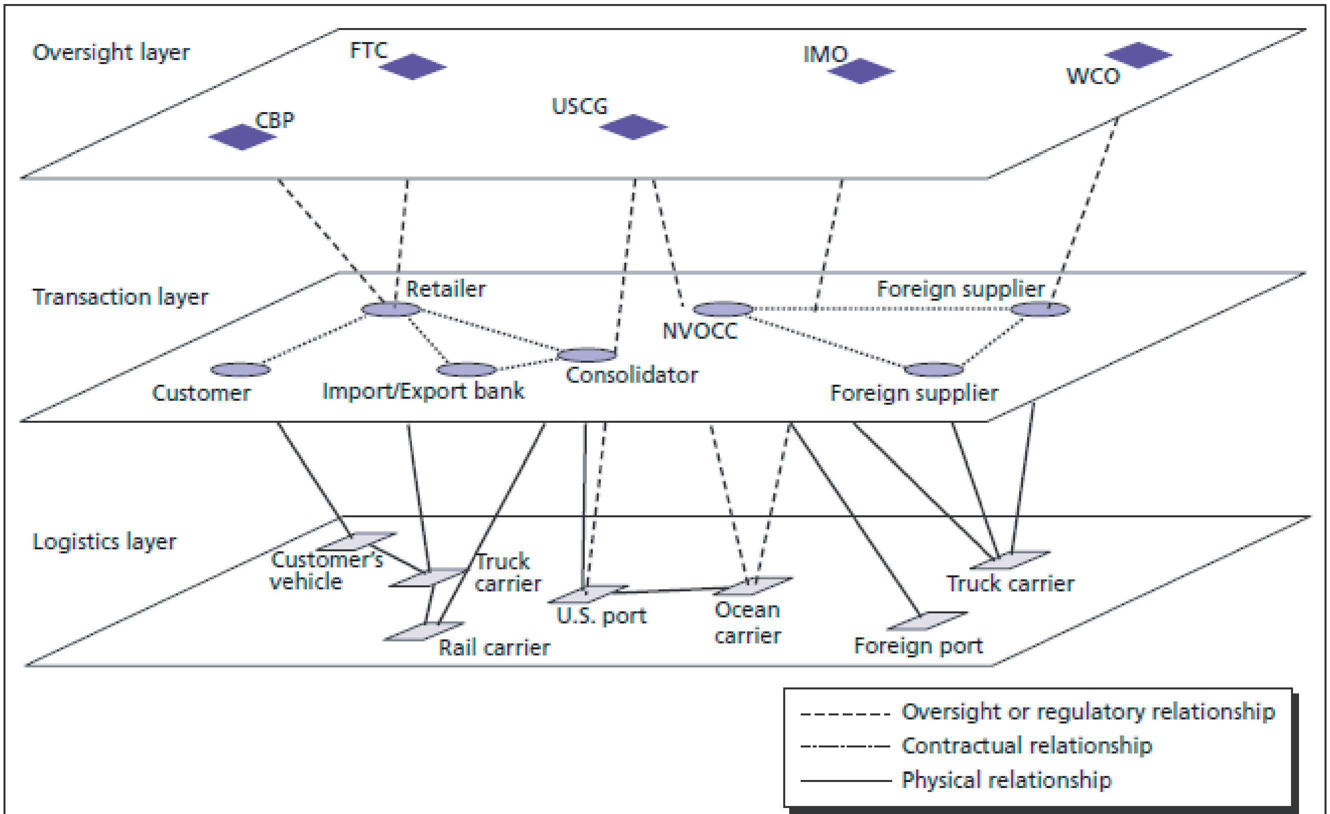
The paper concludes that if most of the supply risk comes from recurrent uncertainty, then increasing quantity from a cheaper, but less reliable source is a better mitigation strategy. However, if most of the supply risk growth comes from an increase in disruption probability, then the firm should order more from a more reliable source and less from a cheaper, but less reliable one.

McKinnon (2006) presented the result of a macro-level assessment of the impact of a failure of the United Kingdom's road transport system due to the effects of the 2000 fuel protest and previous freight road crises on major supply chains. A qualitative extrapolation of the impacts relied on telephone interviews and on expert judgment from brainstorming sessions. The research maps out a timeline of the "creeping" effects of a hypothetical case of a truck stoppage in an entire country. Both immediate, defined as a 5-day impact, and long-term impacts are discussed in some detail.

McKinnon concludes that much of the risk management research focuses on vulnerabilities of individual entities, such as companies or supply chains and the impact of localized disasters such as fire, bad weather, etc., but overlooks the wider effects of systemic collapse/catastrophic failure of critical infrastructure systems. Standard risk mitigation measures such as increasing safety stock, diversifying supply base, and building redundancy into logistical systems are unlikely to afford much protection in such systemic failures while also increasing costs. McKinnon argues that it is mainly the role of the government to work closely with private industry to prepare for such eventualities.

RAND, Inc. (2005) drew attention to supply chain performance measures and how security measures affect supply chains. The study provides broad recommendations for various stakeholders within the supply chain for balancing the need to increase efficiency, while at the same time providing for fault tolerance and resilience through supply chain redundancy. The paper presents a three-tiered structure for the international goods supply chain (see Figure 2-2), consisting of the following tiers:

1. Logistics layer (that includes physical transportation systems and entities such as truck carriers, rail carriers, ocean carriers, etc.);
2. Transaction layer (that procures and distributes goods and is primarily driven by information flow, e.g., customer, retailer, foreign supplier) and;
3. Oversight layer (that provides the policy framework and enforces rules of behavior through standards, fines, and duties).



FTC = Federal Trade Commission; CBP = U.S. Customs and Border Protection; USCG = U.S. Coast Guard; IMO = International Maritime Organization; WCO = World Customs Organization; NVOCC = Non-vessel Operating Common Carrier

Source: Rand (2005).

Figure 2-2. Multi-layered international goods supply chain.

The study uses this structure to analyze the role of different stakeholders in improving supply chain security.

The paper concludes that as a first step the public sector needs to take the lead in bolstering fault tolerance and resilience in the system by creating an appropriate policy environment. Second, security efforts need to address vulnerabilities along the supply chain network trade lanes and not just at port facilities. Finally, the paper recommends that research and development should focus on new technology for low-cost, high-volume remote sensing and scanning that does not compromise efficiency (by imposing delays) and is a reliable measure for ensuring supply chain security.

Nagurney et al. (2002) proposed a multi-level network for conceptualizing supply chain dynamics. The multi-level network consists of a logistics network, an information network, and a finance network and has the ability to model a supply chain response in a competitive environment. Using this model formulation, commodity shipments can be modeled dynamically with the ability to adjust prices over space and time. Commodity prices and flows are brought into a spatial equilibrium.

Rose and Lim (2002) presented several refinements in a hazard loss estimation methodology and applied it to measuring business interruption losses from utility lifeline disruptions following the 1994 Northridge earthquake. They used a combination of primary data tabulation collected through questionnaires, interviews, and telephone surveys and deterministic simulation, which involves the use of mathematical models, such as I–O or linear programming to examine the impact of electricity outage on all sectors in Los Angeles after the Northridge earthquake. The authors critique current methods of loss estimation. In particular, they point out that the application of standard I-O analysis to the estimation of indirect losses exaggerates the levels of losses due to the multiplier effect. Assumptions inherent in the modeling methodology are key to determining the order of magnitude of loss estimation. Consideration of bottleneck effects on other sectors of the economy other than the one being studied can push the estimates upward, whereas consideration of resiliency, or the ability of individual entities and communities to cushion losses, can push estimates downward.

Boarnet (1998) presented the results of a survey of businesses in the Los Angeles-Orange County region following the Northridge earthquake. The survey was conducted with a view to developing insight into the business impact of the infrastructure disruptions as a result of the earthquake. Survey responses from 559 firms in the Los Angeles and Orange County area were collected to provide information on the extent and magnitude of the business losses that could be attributed to transportation system disruptions. It was found that 17 percent of the business losses among the surveyed firms were due to transportation damage. Boarnet concluded that transportation damage is an important factor in economic losses following an earthquake. Interestingly, the research also found there to be no correlation between the distance from the damage due to earthquake and the incidence of transportation losses. This suggests that the transportation network in urban areas is highly interlinked and that firms located some distance from a damaged highway can also be affected by it.

Weinstein and Clower (1998) estimated losses to the Texas economy due to disruption in Union Pacific's (UP) rail service and to safety problems faced by UP in the latter part of 1997. They estimated the impact of these service disruptions in terms of lost sales, reduced output, and higher shipping charges. The study estimated impacts by surveying businesses in six key sectors—chemical industry, agriculture, paper and forest products, building materials, electric utilities, and retail trade. The study included analysis of impacts such as higher prices of intermediate goods that might reduce profits or would cause consumer prices to increase, substitution of more expensive intermediate production inputs for less expensive ones, etc.

2.2.1 Key Conclusions from Research on Disruption and Impact Assessment

- The spatial or geographic scale of disruption will likely have a direct bearing on the magnitude of the economic impact. Thus, for example, the closing of a major port or key links in a land transportation network could have negative impacts throughout the supply chain, assuming little resiliency in moving goods on alternate paths. From a national perspective, however, the economic impacts might be very local (assuming that shippers and carriers can adjust the transportation component of the supply chain to serve the final consumers and thus still provide national benefits). See, for example, Cohen (2002) and Hall (2004).
- A disruption could affect the entire freight system of an area or affect a specific mode. In the situation where a single mode is disrupted, shipments may be transferable to alternative modes. The question then becomes whether or not the alternative modes are suitable for the type of delivery service and cargo carried, they have the capacity to handle the shipments, and they have the required approvals to transport such an unexpected demand in a timely and cost-effective manner.
- The temporal nature of disruption will also have potentially important economic consequences. A short disruption, that is, one lasting a day or up to a week, might cause some temporary or short-term economic loss, but overall would have minimal economic impacts. However, one lasting a much longer time could have severe consequences (see, for example, Chopra et al. 2007; Ito and Lee 2005), depending on how industries and supply chains adjust. It should be noted that temporally short disruptions could also have long-term effects. Thus, network resiliency in placing back into service the necessary facilities and services to move cargo once more becomes an important consideration in assessing overall economic impact.
- The economic impact of severe bottlenecks resulting from disruptions, or from the rerouting of traffic around such disruptions, could affect a wide range of supply chain participants, not just the ocean carriers, truckers, railroads, and shippers that are using the network to transport the goods. Others affected include local labor unions, local retailers, warehousing and distribution providers, and potentially a significant number of consumers and economic organizations throughout the region and/or nation (see, for example, Boarnet 1996; Lewis et al. 2006; Tierney undated). The geographic incidence of impacts can shift over time as well. For example, the 2002 West Coast port labor strike led several major retail chains to shift to using multiple ports, thus altering international cargo flows. The 2011 tsunami in Japan and massive flooding in Thailand have caused many automobile parts makers to rethink the location of their manufacturing plants.
- Different types of disruption could have a range of direct and indirect economic impacts. For example, the removal of one critical link in a network could create a bottleneck that might or might not have important consequences to goods flow. On the other hand, widespread network disruption (for example, due to floods and hurricanes) could have a multitude of overlapping and connected economic impacts (see Abt 2003; Baade et al. 2007; Suarez et al. 2005).
- Network resiliency, whether provided via redundancy in asset supply or by business flexibility in the responsiveness to changed supply and/or demand circumstances, is a very important characteristic of economic impact. If, for example, goods flowing through a particular bottleneck can be rerouted without significant economic costs, the overall economic impact of a bottleneck could be minimal, ignoring for a moment the economic consequences to the local economy (see, for example, Sheffi 2007; Chu and Levinson 2008; and MIT 2008 on freight resiliency planning at the statewide level).
- Assessing economic effects has to take into account the nature of the methodologies being used. For example, a disruption that shifts shipments from rail to truck may require that far more truck drivers be used. Some economic models would see this as a positive impact—more workers are being employed. However, from a user perspective, the system has become potentially less

efficient and not enough drivers and/or highway capacity may exist to handle the increased shipments. In other cases, the methodologies might rely on tools such as scientific surveys (see, Washington State DOT 2008b). Accordingly, the analysis of disruptions may require more of a "tool kit" rather than a one-size-fits-all model, organized within a consistent methodological framework.

- The global goods movement supply chain is a multi-tiered system with various entities, stakeholders, networks, and modes involved that span a huge physical space and by their very nature are susceptible to natural and human-caused disruptions. International supply chains are also intricately interconnected.
- In case of a major event, such as a terrorist attack or an earthquake, standard risk mitigation measures, such as increasing safety stock, diversifying supply base, and building redundancy into logistical systems, may or may not afford much protection from damage. At the same time, the probability of occurrence of such events is small.
- Disruption resistance (security) and tolerance (resilience or recovery) are both important measures in disruption management. These measures have to be balanced with concerns regarding productivity while promising to provide sufficient benefits to justify costs. These measures could include increased electronic surveillance, such as in the case of global container movement, or having back-up suppliers, as in the case of a business that procures raw material, so if a disruption event affects one supplier, there is a fallback. The assumptions regarding resistance and resilience are important in understanding estimates of disruption impacts.
- Various types of economic models can help estimate the potential for losses due to a disruption in the supply chain. These range from simple logical frameworks to complicated dynamic economic simulations. However, it is important to understand the underlying assumptions of these models, particularly with regard to resiliency of, and interdependencies among, businesses and infrastructures. The order of magnitude of loss estimation can be largely affected by these assumptions.

2.3 Available Modeling Tools that Estimate Economic Impacts of Disruptions to the Goods Movement System

2.3.1 Least Cost or Diversion Modeling Tools

Disruption Impact Estimating Tool-Transportation (DIETT)

This tool is designed to generate net national economic impacts as a function of commercial shipments by truck, rail, and waterways. The values estimated by the model include

- Increased cost of freight movement associated with detours and
- Increased inventory costs imposed by the relative uncertainty of deliveries through the detours.

The DIETT Model identifies and prioritizes state-specific transportation choke points (TCPs) according to their potential economic impact on U.S. commerce. The tool can assist state departments of transportation (DOTs) and other state security organizations in identifying and protecting high-value TCPs. The model is executed in MS Access and MS Excel environments. The primary inputs to the model are length of the detour around the TCP, level of congestion (on the original route and detour), and unit cost of shipment. The output is developed through an interconnected and semiautomatic set of functions designed to estimate the least-cost alternative route in case of a disruption and to compute incremental costs. High-value TCPs are located along major commercial transportation routes and are critical points that can affect flow of commodities should a disruptive event occur at these points. Decisionmakers can use DIETT's prioritized set of outputs, along with risk information, to better focus capital resources, security, and emergency preparedness planning. Net economic and societal dislocations are not considered in the model.

Freight Performance Measures (FPM) Data

The FHWA Office of Freight Management and Operations, through a research partnership with the American Transportation Research Institute (ATRI 2010), has developed numerous performance measures for the nation's highway system. Known as the Freight Performance Measures (FPM) Initiative, one element is a data processing tool that determines average operating speeds for trucks that travel on interstate highways. These averages are calculated using GPS technology to collect confidential on-board data from several hundred thousand trucks (https://www.freightperformance.org/fpmweb/user_login.aspx).

Using FPM data, changes in truck speeds can be obtained and diversion analysis can be performed in the case of a disruption to the highway network where more than one interstate corridor is a viable option. With expansion of FPM truck speed data to cover major non-interstate routing alternatives, the data obtained from the FPM Web interface could also assist with visualization and quantification of the level of system disruption resulting from network closures. However, not enough trucks are sampled currently to allow for robust estimates of corridor-specific truck volumes.

Freight Analysis Framework (FAF)

This is a comprehensive multi-sourced and partially modeled database maintained by FHWA and in the public domain (http://ops.fhwa.dot.gov/freight/freight_analysis/faf/index.htm). It identifies the nation's major highway, railway, waterway, and air freight corridors and how different classes of commodity are moved between broad regional origins and destinations (O-Ds). Truck traffic volumes based on these O-D flows are assigned to a detailed representation of the national highway network, and this database can be used to construct scenario analysis by disabling specific links (highway segments, bridges) and nodes (interchanges, intersections). Such scenario analysis can provide key insights such as where the critical nodes are and the number of affected vehicles upstream and downstream of a disruption, the tonnage and dollar values of the commodities affected, and the additional travel time required. Rail and water freight traffic route assignments are not currently available from the FAF, but can be created from the public domain versions of the Railcar Waybills dataset provided on the Surface Transportation Board (STB) Website (http://www.stb.dot.gov/stb/industry/econ_waybill.html), and on the U.S. Army Corps of Engineers' waterborne commerce Website (http://www.ndc.iwr.usace.army.mil/data/datawcus.htm). Mapping these rail and inland barge flows can be accomplished using GIS network representations maintained for the purpose by the Federal Railroad Administration (FRA) and Army Corps of Engineers respectively and found at the Bureau of Transportation Statistics (BTS) National Transportation Atlas Database Website (http://www.bts.gov/publications/national_transportation_atlas_database/2011/). Both a single-mode and a multimodal version (that allows for intermodal connections) of a traffic-routable national freight transportation network, including trans-oceanic linkages, can also be found at the Center for Transportation Analysis' Oak Ridge National Laboratory (CTA/ORNL) Website (http://cta.ornl.gov/transnet/).

Table 2-2 presents a summary of the characteristics of the least-cost or diversion modeling tools that were reviewed for this research.

2.3.2 Industry Supply Chain Response Modeling Tools

Supply Chain Operations Reference Model (SCOR)

SCOR is an off-the-shelf process management tool including three main features—process modeling, performance measurements, and best practices. The SCOR Model has been developed to describe the business activities associated with all phases of satisfying a customer's demand. It can be used for capturing the configuration of a supply chain, measuring its performance, and re-aligning supply chain processes and best practices to fulfill unachieved or changing business objectives.

Table 2-2. Summary of least-cost or diversion modeling tools reviewed.

Tool	DIETT	FPM	FAF
Type of disruption	Any disruption along a goods movement supply chain	Truck flow disruption due to interstate closures	Commodity flow disruption by truck, rail, water, air, pipeline, intermodal, and other transportation modes
Economic impacts measured	Increased cost of freight movement through diversion and increased inventory costs as a result of uncertainty of disruption	Does not explicitly measure economic impacts; however, data can be used as an input to economic impact estimation	Cost of diverted cargo and the delay cost of diversion
Data requirements	State-level TCP databases containing relevant data on mountain passes, tunnels, and bridges; specific datasets (e.g., identifiers, bridge span, detour length, and number of vehicles)	None	None
Typical outputs	List of state-level TCPs, prioritized by net national economic impacts	Truck speeds	Nature and dollar values of affected commodities, congestion, and additional travel time due to disruption
Short- vs. long-term responses	Yes	No	No
Changes in transportation route or facility	Yes	Yes	Yes
Changes in sourcing of goods	No	No	No
Changes in logistics practices	No	No	No

iThink/STELLA (isee systems Software)

This tool provides a graphically oriented front end for the development of system dynamics models. This off-the-shelf software guides a user (typically a business) through the creation of models that simulate business processes and scenarios, pointing out the impacts of a new procedure or policy, and offers an opportunity to fix undesirable outcomes. The stock and flow diagrams used in the system dynamics literature are directly supported in this interface with a series of tools supporting model development. The tool also provides the user with the ability to write equations through dialog boxes accessible from the stock and flow diagrams.

The tool is designed to answer strategic "what if" questions (e.g., what if you increased sales and marketing effort without adding network bandwidth?). The tool has the ability to model a business' entire operations system, using mapping and modeling processes, running simulations and analyses, and communicating through readable dashboards.

Critical Infrastructure Protection/Decision Support System (CIP/DSS)

This project is an integrated joint effort of three Department of Energy (DOE) laboratories, sponsored by the Science and Technology Directorate of the Department of Homeland Security (DHS). The CIP/DSS is a decision support system that can be used by decisionmakers to analyze all 17 of the nation's critical infrastructures and their interdependencies. The model answers questions regarding critical infrastructure stability in times of disruption through the use of "consequence models." Linking critical infrastructures through their strongest interdependencies allows for determination of choke points and vulnerabilities within the nation's systems. The outputs of the consequence models are captured in a consequence database from which "decision metrics" tuned to particular decisionmaker profiles are computed (Bush et al. 2005).

Vensim

Originally developed in the mid-1980s for use in a consulting project, Vensim was made commercially available in 1992. It is an integrated environment for the development and analysis of system dynamics models. Vensim runs on Windows and Macintosh computers and is used for developing, analyzing, and packaging high-quality dynamic feedback models. Features include dynamic functions, subscripting (arrays), Monte Carlo sensitivity analysis, optimization, data handling, application interfaces, and more.

Table 2-3 summaries the characteristics of the industry supply chain response tools reviewed for this project.

2.3.3 Static/I-O Modeling Tools

Transportation Economic Development Impact System (TREDIS)

TREDIS has an economic impact analysis module with an I-O model as its core computation tool. It can be used for all modes, including all forms of passenger and freight transport using road, rail, aviation, and marine facilities (http://www.tredis.com).

PB Regional Impact Scenario Model (PRISM)

PRISM has an I-O model as its core computational tool. PRISM utilizes outputs from full freight network freight flows models to estimate impacts of transportation accessibility improvements across the freight network on industry productivity and output. I-O equations are applied to the

Table 2-3. Summary of industry supply chain response modeling tools reviewed.

Tool	SCOR	iThink/STELLA	CIP/DSS
Type of disruption	Supply chain disruption	Supply chain disruption	Disruption to 1 of 17 of the nation's critical infrastructures
Economic impacts measured	Cost to business of disruption and alternate scenarios	Cost to business of disruption and alternate scenarios	No explicit economic impacts measured
Data requirements	Existing supply chain operations of the business	Existing supply chain operations of the business	Existing supply chain operations
Typical outputs	Business decisions (supply chain response) to changes in business environment	Business decisions (supply chain response) to changes in business environment	"Decision matrix" to determine alternative infrastructure protection strategies
Short- vs. long-term responses	Yes	Yes	Yes
Changes in transportation route or facility	Yes	Yes	Yes
Changes in sourcing of goods	Yes	Yes	Yes
Changes in logistics practices	Yes	Yes	Yes

increases in first order output to derive full regional or state economic impacts. Supply chain cost savings are applied to shippers and consignees based on market conditions, and output is assumed to increase based on underlying demand and constant returns to scale assumptions.

MARAD Port Kit

The MARAD Port Kit estimates the economic value of port activities in easily understandable terms—jobs, income, and taxes generated—which is critical to educating public officials and the general population about the value of the port industry. The kit enables deep-draft ports and other organizations to assess the economic impacts of maritime-related construction and ongoing activities at the national, state, and local levels. The kit

- Quantifies the economic value of deep-draft port activities in readily understandable terms such as employment, income, and tax revenues generated;
- Shows how a deep-draft port is linked to other industries;
- Can be used to investigate "what if" policy simulations (such as shifting trade patterns and dredging policies); and
- Assesses the economic implications of potential investments and changes in business activity.

The results of an economic impact assessment undertaken with the MARAD Port Kit not only show the direct port industry impacts of an investment, cargo flows, or passenger flows, but also identify the total effect on the local region, state, or nation (A. Strauss-Wieder Inc. and Rutgers University 2000). Table 2-4 summaries the characteristics of the I-O modeling tools reviewed for this project.

TREDIS, for example, makes use of the popular IMPLAN I-O data from MIG, Inc. (http://implan.com/V4/Index.php). IMPLAN I-O data is sold at the state, county, and zip code levels for use in a wide range of economic impact analyses. For agencies that have sufficient in-house freight modeling software and expertise, the use of IMPLAN, REMI, or other sources of I-O data as a supplement to their impact studies may also be a cost-effective option to explore. IMPLAN I-O data has similarly been used in the University of Southern California's NIEMO (National Interstate Economic Model), which has been used in recent years to study a number of transportation network disruptions (http://create.usc.edu/2007/05/economic_impact_modeling_and_a_4.html).

Table 2-4. Summary of input-output modeling tools reviewed.

Tool	TREDIS	PRISM	MARAD Port Kit
Type of disruption	Disruption that affects the flow of goods	Disruption that affects the flow of goods	Disruption to a maritime port facility
Economic impacts measured	IO – Multi-regional, state, and county	IO – Multi-regional, state, county, and TAZ	Port facility, state, regional, IO
Data requirements	Good travel demand model or substitute	Good travel demand model or substitute	Information on port industry (investments, cargo flows, etc.) and regional definitions
Typical outputs	Change in employment, personal income, GDP, and value added	Change in employment, personal income, GDP, and value added	Impact on economy–jobs, output, income, and taxes
Short- vs. long-term responses	Yes	Yes	Yes
Changes in transportation route or facility	No	No	Yes
Changes in sourcing of goods	No	No	Yes
Changes in logistics practices	No	No	Yes

2.3.4 Dynamic Economic Simulation Modeling Tools

Long-term Inter-industry Forecasting Tool (LIFT)

LIFT is a full macroeconomic model of over 800 variables. It combines an inter-industry (I-O) formulation with extensive use of regression analysis and employs a "bottom-up" approach to macroeconomic modeling. Its macroeconomic "superstructure" contains key functions for household savings behavior, interest rates, exchange rates, unemployment, taxes, government spending, and current account balances.

The tool's demand/production block uses econometric equations to predict the behavior of real final demand (consumption, investment, imports, exports, government) at a detailed level. Then, the detailed predictions for demand are used in an I-O production identity to generate gross output (total revenue adjusted for inflation). LIFT's approach to projecting industry prices is similar, involving behavioral equations that estimate each value-added component (e.g., compensation, profits, interest, rent, indirect taxes) for each industry.

Regional Economic Models, Inc. (REMI) Model

REMI is an integrated modeling tool that combines I-O modeling methodology with an econometric model, where underlying equations and responses are estimated using statistical techniques. The estimates are used to quantify the structural relationships in the model. The overall structure is that of a macroeconomic model with features of a market equilibrium model for the labor sector, as well as features of the new economic geography related to inter-regional competitiveness. It is empirically calibrated on the basis of region-specific data.

Table 2-5 summarizes the characteristics of the econometric/simulation modeling tools reviewed for this project.

2.4 Empirical Estimations of Economic Impacts of Disruptions to the Goods Movement System

2.4.1 Least-Cost or Diversion Model Applications

ATRI (2010) presented an analysis of FPM data for the impact on truck traffic of the closure of I-40 near the North Carolina-Tennessee border in late 2009 and early 2010. Three methods of analysis were used for analyzing truck flows during two, 10-day study periods (before and after the closure) as follows:

Table 2-5. Summary of econometric/simulation modeling tools reviewed.

Tool	LIFT	REMI
Type of disruption	Disruption to container shipment at an international port of entry	Disruption that affects the flow of goods
Economic impacts measured	Overall impact on the IO economy	US: multi-regional, state, county
Data requirements	Data from federal govt. on container imports arriving at individual ports nationwide, all modes	Good travel demand model or substitute
Typical outputs	Reduction in GDP	Change in employment, personal income GDP, and value added
Short- vs. long-term responses	Yes	Yes
Changes in transportation route or facility	Yes	No
Changes in sourcing of goods	Yes	No
Changes in logistics practices	Yes	Yes

- Average travel speed of trucks and truck demand for I-40,
- Spot speed and roadway utilization that identifies specific points where trucks are operating, and
- Freight flow information that identifies trends in truck movement.

The research presents, by means of maps and graphics, several variables such as truck flows, system speeds, spot speed analysis to assess alternative routing during the closure of the I-40 segment, and freight flow diagrams that contrast truck flows before and after the incident. This report acts only as a demonstration tool that highlights capabilities and applications of FPM data and analysis. To determine delay costs, researchers could calculate total hours of delay and increases in operational costs for those trucks that use the I-40 corridor as part of regular operations using the FPM program. This method can be applied to understand how well prepared a particular facility is to respond to a disruption.

2.4.2 Industry Supply Chain Response Model Applications

Wilson (2007) investigated how a transportation disruption affects the supply chain performance of a traditional supply chain and a vendor-managed inventory (VMI) system. The author also discusses how individual supply chain risks are connected and suggests strategies for mitigating the risk from transportation disruption. The model uses a system dynamics simulation software, iThink, to estimate the outcomes and impacts of various types of disruptions. Disruptions are classified by the location in the supply chain echelon (e.g., between warehouse and retailer, between supplier and warehouse, etc.). The simulation compares the impacts on a traditional supply chain versus those on a VMI. The author models a period of 600 days with a 10-day disruption occurring at day 200. The model utilizes data such as customer demand, inventory policy, processing and transport capacity, operational details, and type of disruption. The metrics used to evaluate the performance of the supply chain are unfilled retail customer orders, maximum number of goods in transit, and maximum and average inventory levels.

The study finds that a disruption between a Tier 1 supplier and the warehouse or distributor creates the most problems within a traditional supply chain structure. Using a VMI reduces some of the impact. A VMI involves sharing customer-demand information and retail and warehouse inventory positions with the Tier 1 supplier. Hence, the benefit of disruption impact mitigation would have to be balanced with risk of dissemination of intellectual property. Another strategy for mitigation of this risk is carrying additional inventory or having a redundant supplier, although some of these strategies translate into additional cost and may have limited impact in cases where the redundant supplier is also impacted by the disruption.

Lewis et al. (2006) proposed a Markov decision model to solve the inventory management problem faced by a firm operating an international supply chain that utilizes a seaport prone to unexpected closures. The problem of unexpected seaport closures results in a need to optimize overall inventory management costs and the costs of unfulfilled demand, both of which are impacted by variability in product delivery lead times resulting from unexpected seaport closures. The model can be used to determine both the probability of seaport closures and the expected duration of closures. Furthermore, the study examines how these cost impacts may be mitigated by the availability of additional, post-disruption emergency processing capacity. The model assumes that port closures lead to ships waiting to offload containers (instead of rerouting) and uses a simple deterministic queuing approach to model port freight processing dynamics. The model uses firm-specific data such as supply chain lead time, value of contents of a 40-foot container, holding cost, penalty for unfilled demand, units of work/day, and assumptions about seaport closure and reopening probabilities.

The study finds that the length of a seaport closure affects a firm's supply chain more negatively than does the probability of closure. Hence, contingency planning (from the firm's perspective) and minimizing the duration of a closure, in the event of one (from the government's or port authority's perspective) are critical. The paper also concludes that holding and penalty costs increase more than linearly with port utilization, indicating a need for increasing government investments in processing capabilities and contingency planning (such as rerouting of freight to other ports of entry) for highly utilized ports.

Dauelsberg and Outkin (2005) present a model of economic impacts arising from disruptions to critical infrastructures. Disruptions and their economic consequences are modeled as non-equilibrium events where the interdependent nature of various infrastructures allows event and disruption propagation from one infrastructure to another. The Critical Infrastructure Metropolitan Model is a set of critical infrastructure subsectors modeled in a system dynamics framework. Disruptions and their economic impacts are modeled as non-equilibrium events, where the independent nature of different infrastructures allows event disruption propagation from one infrastructure to another. In addition to lost sales, the model computes lost value-added by computing per capita gross state product and factoring it by the number of days of worker absence due to death, illness, or quarantine as a result of the disruption. This approach is deemed superior to a traditional I-O approach where equilibrium conditions are implied and are often calibrated to annual data in order to capture long-term trends and permanent change only, smoothing out the short-term dynamics.

2.4.3 Static/I-O Model Applications

Ham et al. (2005) proposed a model to estimate inter-regional economic impacts of disruptions caused by major events (such as earthquakes) to intermodal transportation hubs (such as the Midwest). The model takes into account inter-regional commodity flows by sector and mode on U.S. inter-regional transportation networks. It computes changes in mean shipment length as a result of disruptions in transportation networks caused by the disaster event and estimates the modified value of inter-regional shipments as a result of increased shipping costs.

The analysis uses a transportation network model (a modification of the traditional four-step transportation planning model) to estimate the impact of route changes in the event of a disruption to key links in the transportation network. A simple least-cost routing method is used to estimate alternate paths. The model then goes on to estimate the change in the value of inter-regional commodity flows as a result of the disruption. It assumes that the net loss in the inter-regional commodity flows is converted to intra-regional commodity flows due to increased shipment costs as a result of disruption to the network. It also assumes a shift of commodities from highways to railways. An application of the model to a hypothetical case of an earthquake in the New Madrid Seismic Zone is presented in the paper.

The model uses commodity flow data collected by the U.S. Census Bureau in cooperation with the Bureau of Transportation Statistics. Data for the transportation network was based on the National Transportation Atlas Database. A simplified version of the existing railway network was used in the model.

The transportation network model may be applied to identify critical sections of the network and analyze post-event reconstruction strategies. The economic impacts estimation method may be used to estimate the indirect impacts of a catastrophic event on inter-regional commodity flows. Changes in demand after an event also need to be taken into consideration in the event of a catastrophic event, but have not been included in this model.

2.4.4 Dynamic Economic Simulation Model Applications

Rose et al. (2007) estimated the economic impacts on the U.S. economy of a 1-year halt in all imports from the rest of the world in response to an external threat to the United States. The analysis uses the REMI Model with an I-O model at its core. Different data and refinements are needed for various types of closures—shutdown of imports, exports, international travel, and immigration. Policy variables that represent the direct impacts of simulated events are determined. Industry sales/international exports for each sector, data on levels of tourism, and total expenditure by international tourists within the U.S. regional breakdown of expenditure statistics are other inputs to the model. The net loss of GDP resulting from a complete shutdown of U.S. borders to people and goods for a period of 1 year is estimated to be close to $1.4 trillion measured in 2006 dollars.

Arnold et al. (2006) summarized the structure and economics of the U.S. container port industry and its significance to U.S. merchandise trade. They estimated economic losses of disruptions in that traffic by investigating two hypothetical scenarios involving closure of the ports of Los Angeles and Long Beach.

The analysis of economic losses resulting from disruptions in container traffic was performed using the University of Maryland's LIFT Model. Estimates of economic losses for the 2002 closure of the Los Angeles and Long Beach ports were performed and compared to other estimates for that event. The LIFT Model is described as being superior to other estimating techniques, because it takes an inter-industry view of disruption rather than a business-centric view, and hence assumed that the economy as a whole makes adjustments in response to adverse supply shocks, thus helping contain losses. In the case of a supply disruption, businesses adjust in various ways. In the case of U.S. imports, the blocked imports could

- Enter the country from other open ports with temporary adjustments and capacity increases at those facilities,
- Be replaced, in part, by U.S. production of those goods (with U.S. producers responding to the increase in price by increasing production),
- Be compensated for by inventory draw downs.

Models estimating economic losses should take into consideration these adjustments in order to make a more accurate assessment of the impact. However, there is uncertainty in this approach as well. For instance, it is difficult to know the ability of importers to find alternative routes for bringing imports into the United States. Industries and companies that use just-in-time inventory management could be disproportionately upset by disruption to imports. Little data is available on which industries use this method of inventory management. Lastly, the outcome for GDP will depend in part on the speed with which increases in import prices are reflected in the prices of the final goods and on the Federal Reserve's response, both of which are uncertain.

Tsuchiya et al. (2007) propose an analytical framework to estimate the indirect economic impacts of disasters on a multi-regional scale. The model considers both highway and rail networks and includes freight as well as passenger movements. The model is integrated with a transportation network model.

The inter-regional spillovers of direct damage due to disruption are estimated using a spatial computable general equilibrium (SCGE) model. In order to be used/applied, the model requires an inter-regional I-O table containing data on trade flows between regions, as well as railroad and highway information. It also utilizes other inputs such as production capacity rate, rate-based transportation cost, etc. Additionally, a transportation network model is required to estimate delays on the system after a major incident. Delays and hence loss estimation can be measured in the short term as well as in the long term.

The model was applied to the Niigata-Chuetsu earthquake of 2004. Earthquake-related damage to transportation networks was considerable and widespread. Countermeasures were needed to reduce negative spillover effects to regions apparently unaffected by the disaster (i.e., those that sustained no physical damage as a result of the earthquake).

2.5 Construction of Freight Cost Matrices

For the purposes of simulating both modal and market competition, a consistent treatment of transportation costs is required. This means that the costs computed for each mode, and for each source-market pair, should include the same generically defined set of cost elements. For the most part, freight costs are obtained from the following three sources:

1. Freight rates based on averaging over a large number of individual shipping contracts,
2. Statistically based freight costing or freight rate models, and
3. Component-by-component constructed engineering cost models.

Costs are usually derived on a commodity- and mode-specific basis. Cost and rates/fees are not the same. Rates and fees charged by freight providers generally include a profit margin, which varies by load, commodity, client size, and shipment characteristics, along with the competitive situation. However, rate and fee information can be easier to obtain than cost information. For example, published tariffs include some of this information.

Statistical Cost Models

These costs are usually based on regression modeling. The models use either cross-sectional or time-series data for calibration purposes and typically include travel distance or distance-based average operating cost, travel time, and one or more measures of service quality, notably measures of service reliability (such as on-time arrival percentage, or standard deviation of delivery times). There are many examples of regression-based freight costing models. Commercially available products include Global Insight's COSTLINE© family of rail and barge costing models (http://www.ihsglobalinsight.com/gcpath/Costline.pdf) and Commonwealth Logistics Rail Costing System© (http://commonwealthlogistics.com/). Benson, Vachal, and Byberg (1999) use historical data to estimate container rates for agricultural commodity cargos. Rate calculators based on this work can be found on the IODA's Ocean Rate Bulletin Website (see http://www.ams.IOda.gov/tmd/Ocean/calculatIons.htm).

Engineering Cost Models

These models often take the form of a detailed spreadsheet model summing costs over a mode's principal cost components and producing a total dollar valued cost per ton or per ton-mile. Examples include ITIC-IM, the U.S.DOT's Intermodal Transportation and Inventory Cost Model (FRA 2005), ORNIM, the U.S. Army Corps of Engineers Ohio River Navigation Investment Model (ORNL 2001), STB's Uniform Railroad Costing System (URCS) software, and the Truck Load Analysis Model developed by Berwick and Faroog (2003). Each of these models includes a wide range of logistics as well as pure "transportation" costs, and each offers a means of reconciling fixed and variable costs for economic analysis purposes. An ongoing TRB project, NCFRP Project 26, is looking in depth into freight costs.

2.6 Summary

Table 2-6 summarizes the supply chain and economic impact models reviewed for this project. Numerous important issues for economic impact modeling surfaced from this literature review, including the following:

- **Duration of disruption** (e.g., day[s], week[s], month[s], year[s])—The extent and nature of the response to such disruptions will vary depending on how long the disruption lasts and how widespread the scope of the disruption. It is important to recognize that disruptions may have both short- and long-term impacts. When possible, it is best to assess and articulate both of these impacts using a common methodological framework.

Table 2-6. Summary of models reviewed.

	Supply Chain Models		**Economic Impact Models**	
Characteristics	Least Cost/Diversion Models	Logistics and Industry Response Models	Static/Input-Output Models	Dynamic/Econometric Models
Representative Tools	DIETT, FPM, FAF	PDRM, CIP/DSS, SCOR, iThink/STELLA	TREDIS, PRISM, MARAD Port Kit	REMI, LIFT
Empirical Applications	ATRI (2010), Freidman (2005)	Wilson (2007), Lewis et al. (2006), Dauelsberg et al. (2005)	Ham et al. (2005)	Rose et al. (2007), Arnold et al. (2006), Tsuchiya et al. (2007)
Data Requirements	Readily available by mode from published sources	Quantitative or qualitative; quantitative analysis can utilize statistical or econometric results	Requires commodity- and industry-specific freight data to be fully effective	Requires substantial data and multiple iterations of analysis – time series, cross-section, or panel data can be used
Economic Variables	Unit freight and inventory costs (e.g., per ton mile)	Changes in supply chain response (inventory management, sourcing, routing, etc.)	Changes in final demand (final industry sales or output, capital expenditures, operating expenditures)	Explanatory variables include direct impacts, control variables, length of disruption, geographic location, etc.
Direct Impact Representation	Yes	Yes	Yes	Yes
Indirect Impact Representation	No	Yes	Yes	Yes
Typical Outputs	Unit freight and inventory costs (e.g., per ton mile)	Changes in output; industry location response variables	Output, value added, inter-industry sales, employment, income	Output, value added, inter-industry sales, employment, income, others as specified
Representation of Uncertainty	No	Varies	No	Yes
Cost of Use	Low	Can be high	High if customized; low if off the shelf	High because labor intensive
Application to System Level Analysis and Specific Modes	Yes	Yes	Not mode specific, but commodity specific	Yes, if specified
Application to Region Level Analysis	Usually average unit costs for U.S. as a whole	Yes	Yes	Yes
Availability of Model (Public Domain/Private)	Public, private if customized	Public or private	Usually public domain	Usually public or needs to be developed
Ease of Use	Moderate	Variable	Moderate	Low

- **Mode**—Cargo can sometimes shift to alternative modes when disruptions occur. The extent and nature of this shift will depend on many factors, such as whether the alternative mode serves the same geographic markets, the degree of redundancy in alternative mode, the flexibility in a shipper's business practices, the economics of goods movement for different modes (e.g., low value-added bulk goods moving by barge will not likely shift to truck, but rather to rail as the next best alternative), and the available capacity and suitable cargo carrying approvals on alternative modes.
- **Value of commodities being shipped**—Whether goods can be shipped economically via other modes depends, in addition to the availability of service, on the value and nature of the cargo itself. High-value commodities or commodities that are otherwise time sensitive, such as air cargo, may not economically be shifted to slower modes. This can have major negative

effects on some parts of the country such as the Pacific Northwest, where high value-added electronics and computer parts manufacturing occurs.

- **Geographic area involved**—The spatial level can affect the degree of impact, as well as the types of models used in the assessment. The time dimension is especially important and merits some extra discussion. In the short run, impacts may be smaller under "normal" supply chain conditions, because there will be inventory to fall back upon. In the long run (i.e., for very long-term disruptions), the impacts may also be relatively small in an absolute sense, as both supply chains and industries may adjust. However, the spatial and distributional impacts may be significant to the extent that adjustments become permanent. For example, industries might permanently change their production locations or supply chain paths and routing may permanently change (shippers may shift to other modes, other ports of entry, etc.). These would have major regional economic impacts, for example, by shifting production offshore or shifting some warehousing and distribution activities from one coast to another.

In the medium run, impacts might actually be greatest if long-run adjustments are not yet established but inventories are drawn down and real supply chain disruptions begin to occur.

CHAPTER 3

Analysis Framework

3.1 A Five-Step Decision/Analysis Process

The sequential five-step process shown in Figure 3-1 was developed as part of this research as a comprehensive and practicable framework for evaluating a wide range of freight network disruption events and their many possible economic impacts. The following sections describe each step in turn and break up the flow chart in the figure into its separate and sequential components. This framework represents the components of an in-depth analysis methodology for analyzing in great detail the economic costs of a transportation system disruption.

3.1.1 Step 1: Define Direct Freight Transportation Network Impacts

This initial step identifies the direct, immediate physical effects of a network disruption (see Figure 3-2). This includes identification of the specific transportation facilities affected and the associated modes of transport within, into, and out of the region impacted. The timeframe and the geographic extent of the disruption are also determined. The timeframe here represents the time it takes for the network to return to something resembling its pre-disruption condition. The geographic extent represents the size of the region that is directly impacted by a change in transportation network condition and throughput capacity.

The disruption may affect one or more specific highway, rail, waterway, or pipeline network links. It may also take the form of damage to, or loss of, storage space, docking space, or cargo handling equipment at one or more seaports, airports, or other multimodal freight transfer facilities in the affected area.

Data Needs

An inventory of impacted facilities needs to be assembled and site reports collected in those cases where an assessment is being attempted after a disruption has occurred (as opposed to an anticipatory study of potential disruptions). This may mean searching through various data sources, as well as tracking the timeline associated with the return of specific transportation facilities to either partial or full operational status (or a record of their subsequent loss to future use). In some cases, on-site interviews to obtain the best possible understanding of the nature and extent of the physical and operational disruptions will be extremely helpful. For longer term disruptions, daily situation reports may have been used to identify potential traffic bottlenecks.

3.1.2 Step 2: Identify Current and Future Affected Network Flows by Facility and Link

Step 2 identifies current and future affected network flows by facility and link (see Figure 3-3). Various more or less severe impacts on day-to-day operations are possible, from a rerouting of local

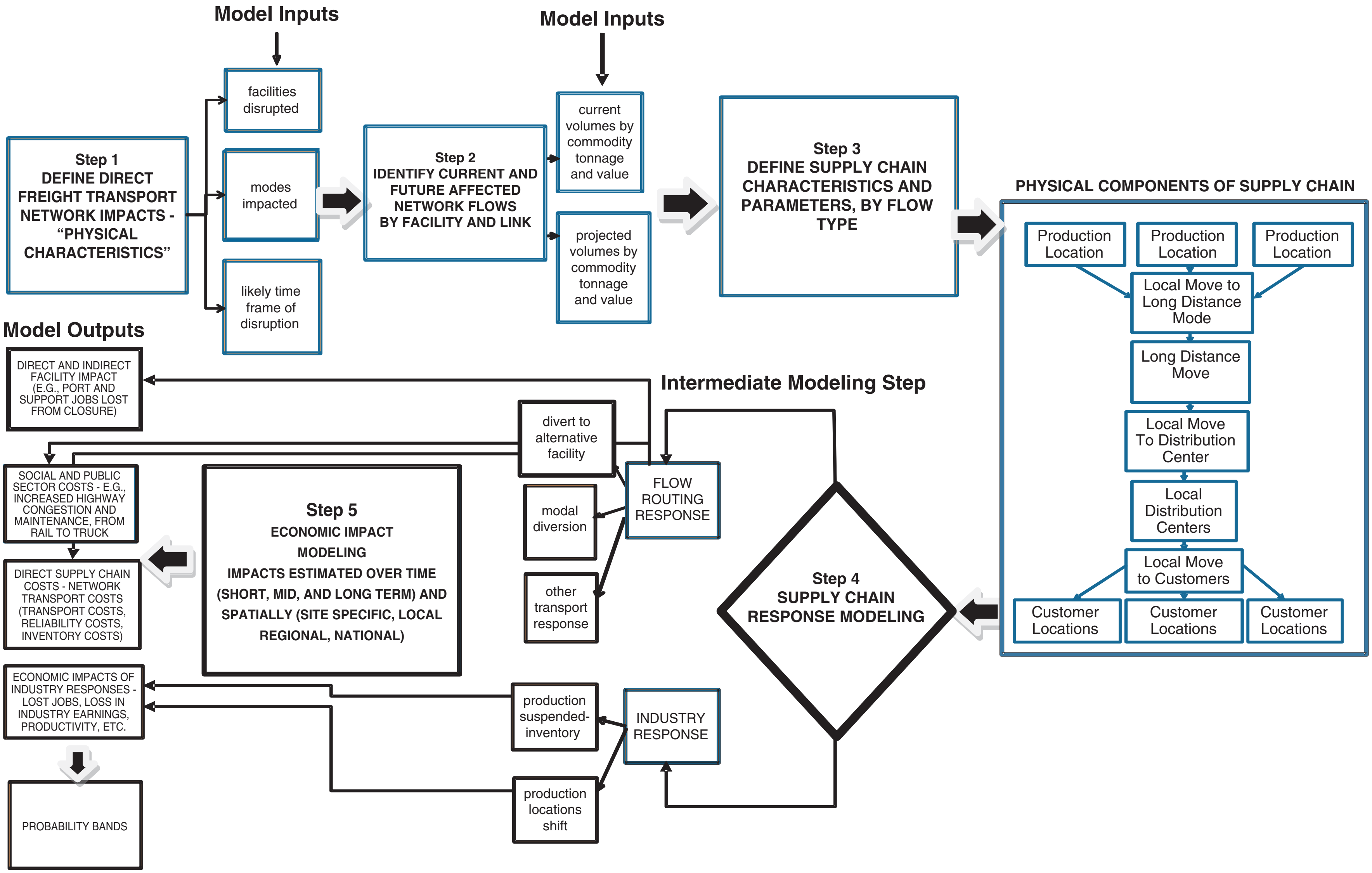


Figure 3-1. Five-step decision/analysis tool for studying freight network disruptions.

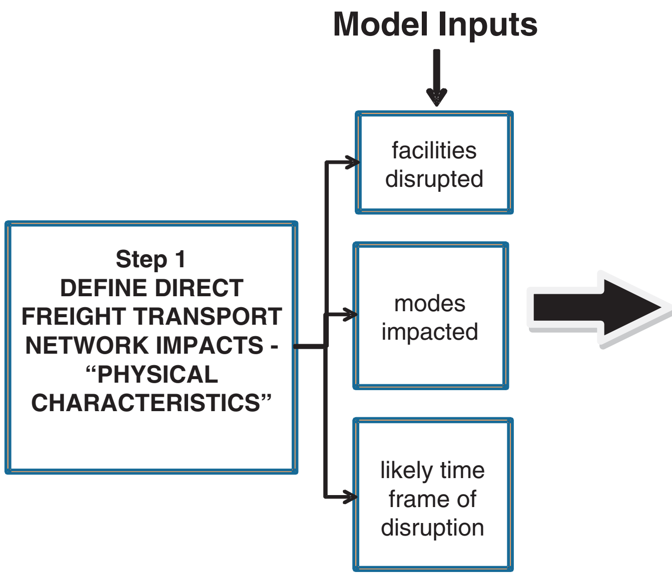


Figure 3-2. Define direct freight impacts.

or through traffic or a reassignment of vessels to other berths or terminals, to shifts in operating times to avoid increased on-network congestion, to a net loss of cargo docking/storage/cargo transfer capacity at ports and land freight consolidation/break-bulk terminals. Longer term disruptions involving major damage to port or other terminal facilities may lead to truck, train, vessel, or aircraft rerouting to other locations and to a resulting drop in local freight traffic volumes. It may also be necessary to account for disruptions to pipeline product flows.

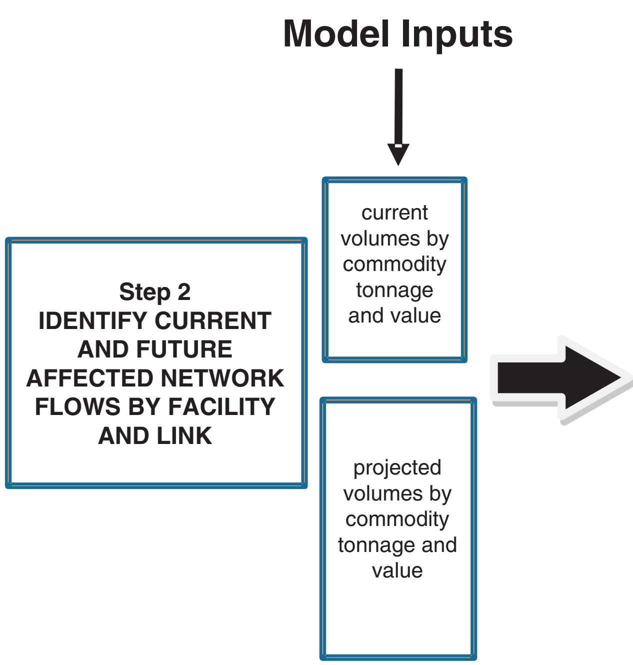


Figure 3-3. Identify current and future affected network flows.

Data Needs

The principal data needs at this step are the following:

- A link-node representation of the regional transportation network.
- Time series data on regional freight traffic counts (or better still, origin-destination and route-specific traffic movements) from before and after the event. Data on projected/forecast flows over these same network links would also be useful.
- Data on the locations and the pre- versus post-disruption throughput and storage capacities of local and regional truck, rail, waterway, and air freight trans-shipment centers in the region.

3.1.3 Step 3: Define Supply Chain Characteristics and Parameters by Flow Type

Freight supply chains, which involve moving a commodity from production site to final customers, differ a good deal by commodity transported, including whether the cargo involves shipping raw materials, intermediate, or finished goods. Both physical and financial/institutional adjustments will often be required, typically leading to higher total transaction costs. Physical aspects of supply chains (see Figure 3-4) can vary from simple single mode, direct source-to-market linkages, to multi-link and multimodal linkages involving one or more cargo consolidations, breakups, and/or vehicle/vessel transfers. The true costs of disruptions to freight deliveries in the latter case are very difficult to estimate, beyond the effects on the immediately impacted

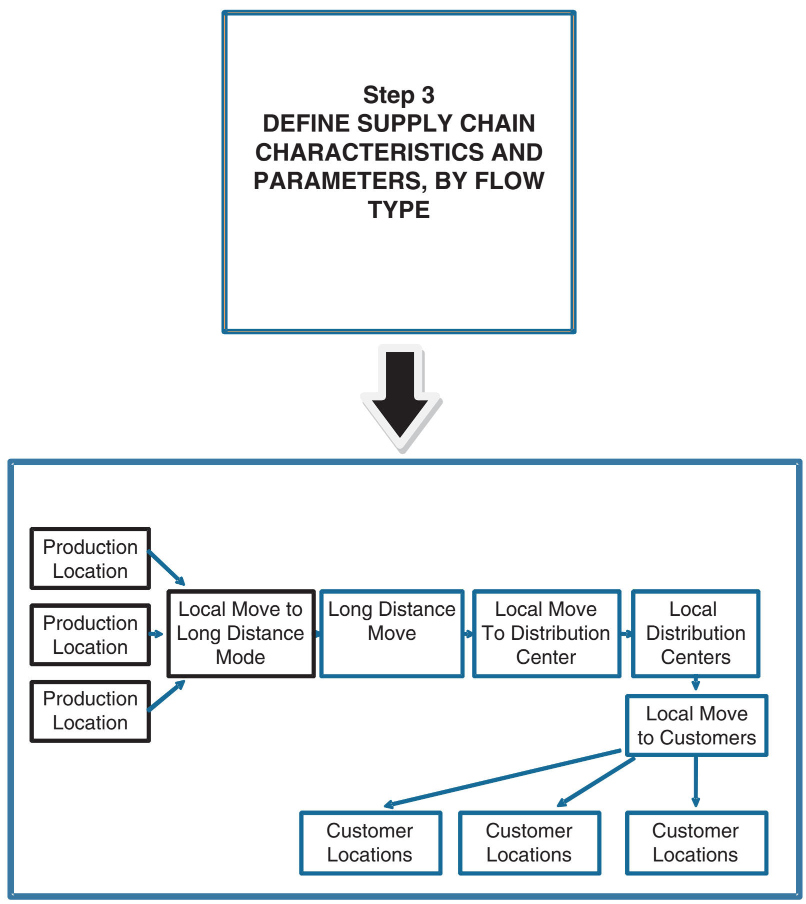


Figure 3-4. Define supply chain characteristics and parameters.

leg in the physical supply chain. However, this may be sufficient for most purposes. Not often captured to date, but potentially costly, are the effects on freight handling costs as well as inventory carrying costs from unreliable service delivery times. Also not generally considered are the costs of renegotiating freight deliveries by other means. Shippers, or their freight forwarders or logistics service providers (3PLs), will often need to either change their consignee designations or issue new contracts for both drayage or rail land transfers. Shippers and carriers may have to change their routing documentation on the cargo to maintain ownership and liability insurance. Contract terms between shippers, carriers, and terminal operators may need to be modified. If international cargo is involved, U.S. Customs may need to shift the port of entry, potentially involving multiple cargo releases and re-manifesting of in-bond and other classes of cargo. Such financial costs may be relatively short-lived, but may be significant for shippers and carriers if current contracts cannot be met.

Data Needs

Data on the physical and financial transaction costs that result from a transportation network disruption are needed, including administrative and other logistics costs that are encountered, above and beyond any direct shipper-carrier negotiated transportation rates.

3.1.4 Step 4: Supply Chain Response Modeling

Step 4 models the response of the supply chain to disruptions (see Figure 3-5). This is the most challenging of the five steps in the process, with limited empirical evidence available currently from the literature and with much depending on the specific industrial sector studied as well as the range of logistical arrangements possible by the firms operating within each sector.

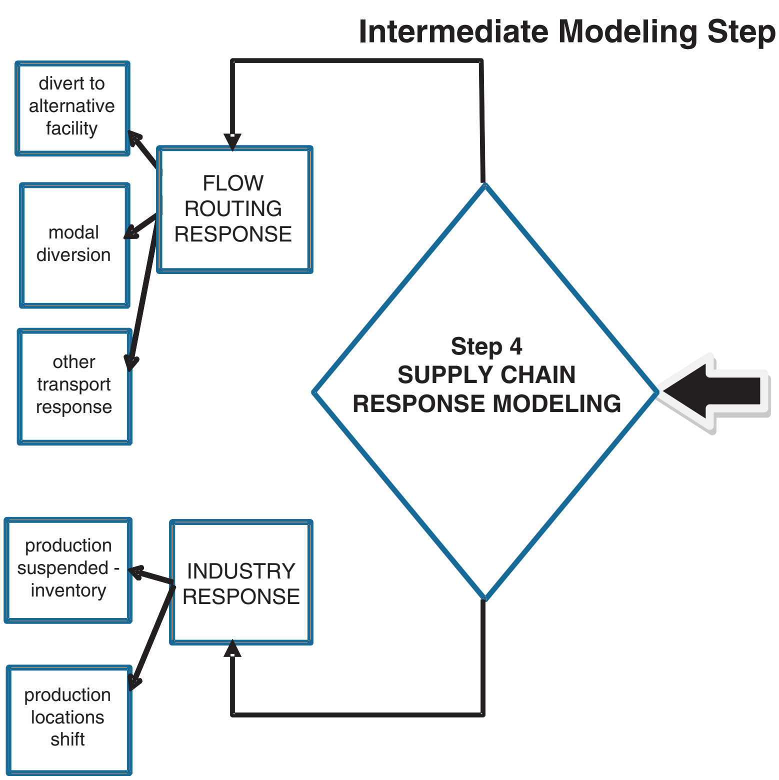


Figure 3-5. Supply chain response modeling.

Data Needs

There are the following data needs:

- Users can assume average diversion distances and travel times based on knowledge of the network for all commodities (e.g., similar to the DIETT Model procedure). Additional time and cost penalties may be built-in to reflect rescheduling (deferred) shipments and also overtime cost penalties, possibly suitable for the high-level methodology, but this entails substantial error and crude approximations.
- Users can assume differential diversion distances and travel times by mode, distance travelled, and product value (e.g., similar to DIETT Model procedure). Additional time and cost penalties may be built-in as above. This approach is possibly suitable for the high-level methodology, but entails error and approximations. Commodity-specific assumptions may reduce the extent of approximation error.
- Survey-data-based response modeling of shippers and carriers. Users may assume similar behavioral responses to those collected from previous surveys and reported in the literature, and matched to similar disruption situations. Highway network rerouting and truck load consolidation models make similar assumptions in a planning situation to real world trucking responses, such as share diverted, share rescheduled, etc., based on matching characteristics.

Modeling Possibilities

Depending on the geographic extent and duration of the network disruption, analytic modeling will be needed to address the following topics:

- Freight flow delivery responses
  - Short-term rail, barge, truck, and air freight traffic rerouting models, including the possible rerouting of trans-continental landed trade or ocean vessel movements;
  - Short-term mode shift models from, for example, barge to rail or to truck;
  - Short-term source-market restructuring of origin-destination flows;
  - More permanent restructuring of origin-destination flows.
- Industry responses
  - Inventory draw downs,
  - Reduced or suspended production levels,
  - Shifts in the location(s) of production.

Depending on their duration and extent, any shifts, re-locations, suspensions, or delays in production may have significant impacts on carrier, shipper, and receiver profits. More permanent forms of origin-destination freight delivery channel restructuring could have even greater impacts.

3.1.5 Step 5: Economic Impact Modeling

This step models the economic impacts of network disruptions (see Figure 3-6). The extent and depth of economic impact modeling will depend heavily on Step 4—i.e., what is assumed about supply chain responses to disruptions, or what is estimated based on more in-depth modeling. For the high-level methodology presented in Chapter 5, relatively simple and straightforward assumptions and rules of thumb are developed and applied. Figure 3-7 illustrates the basic concept of the types of assumptions and methodologies that could be employed at each stage of the analysis process, for both a high-level methodology and an in-depth methodology. As seen in the figure, economic impacts for the high-level methodology would focus on simple rules of thumb and short-term, direct impacts. Rules of thumb would include unit transportation and inventory costs, jobs lost per container for direct facility disruptions, and "elasticities"

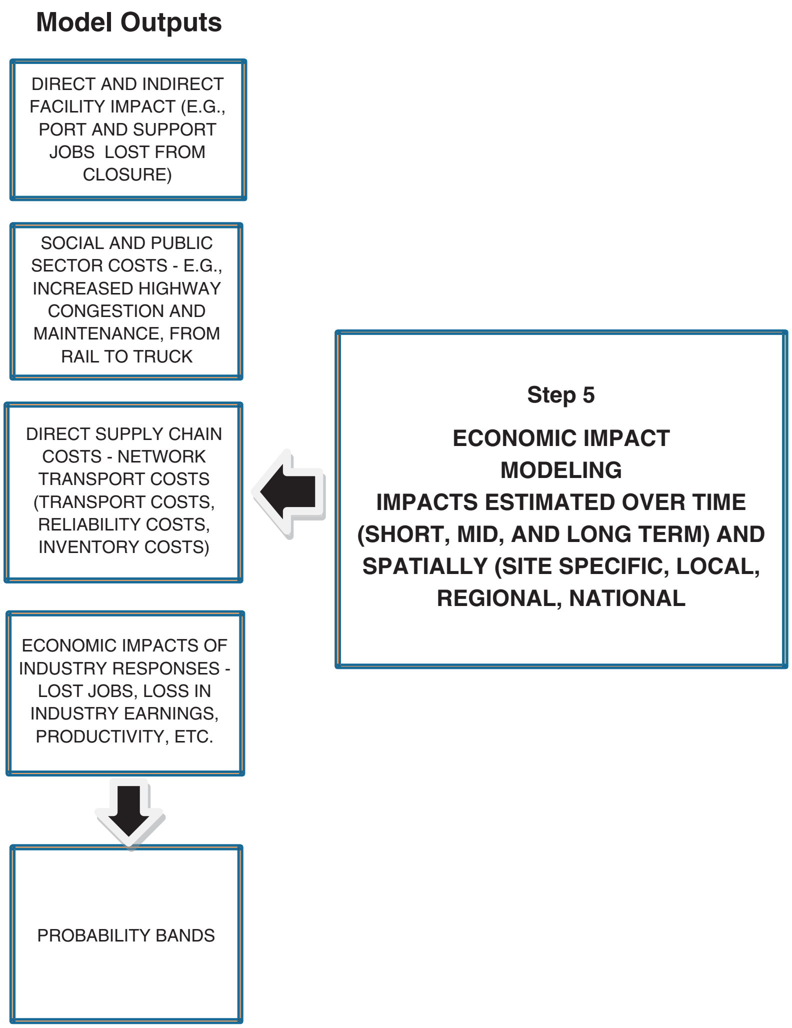


Figure 3-6. Economic impact modeling.

that could express the average relationship between increases in transportation costs or delayed delivery costs, and industry output and sales revenues.

The types of data, analysis tools, and the outputs will necessarily differ depending on whether the high-level methodology or the in-depth methodology is being used. A high-level methodology may not allow detailed analyses of supply chain or industry behavior responses. An in-depth methodology should include a more rigorous and nuanced assessment of this type of supply chain behavior. For example, for the supply chain response component in a high-level methodology, one could use simple route choice or modal diversion curves or sketch modeling, whereas more detailed logistics or industry response modeling would be used for an in-depth methodology.

Data Needs

For the high-level methodology, input data requirements would be kept to a minimum (e.g., no sophisticated network modeling of freight flows would be conducted). Instead, reasonable assumptions would be made about length of detours or diversions, shipping delays, and modal diversions. These, in turn would provide simple measures to which economic impact rules of thumb could be applied (e.g., if we know that transportation costs for a particular commodity will

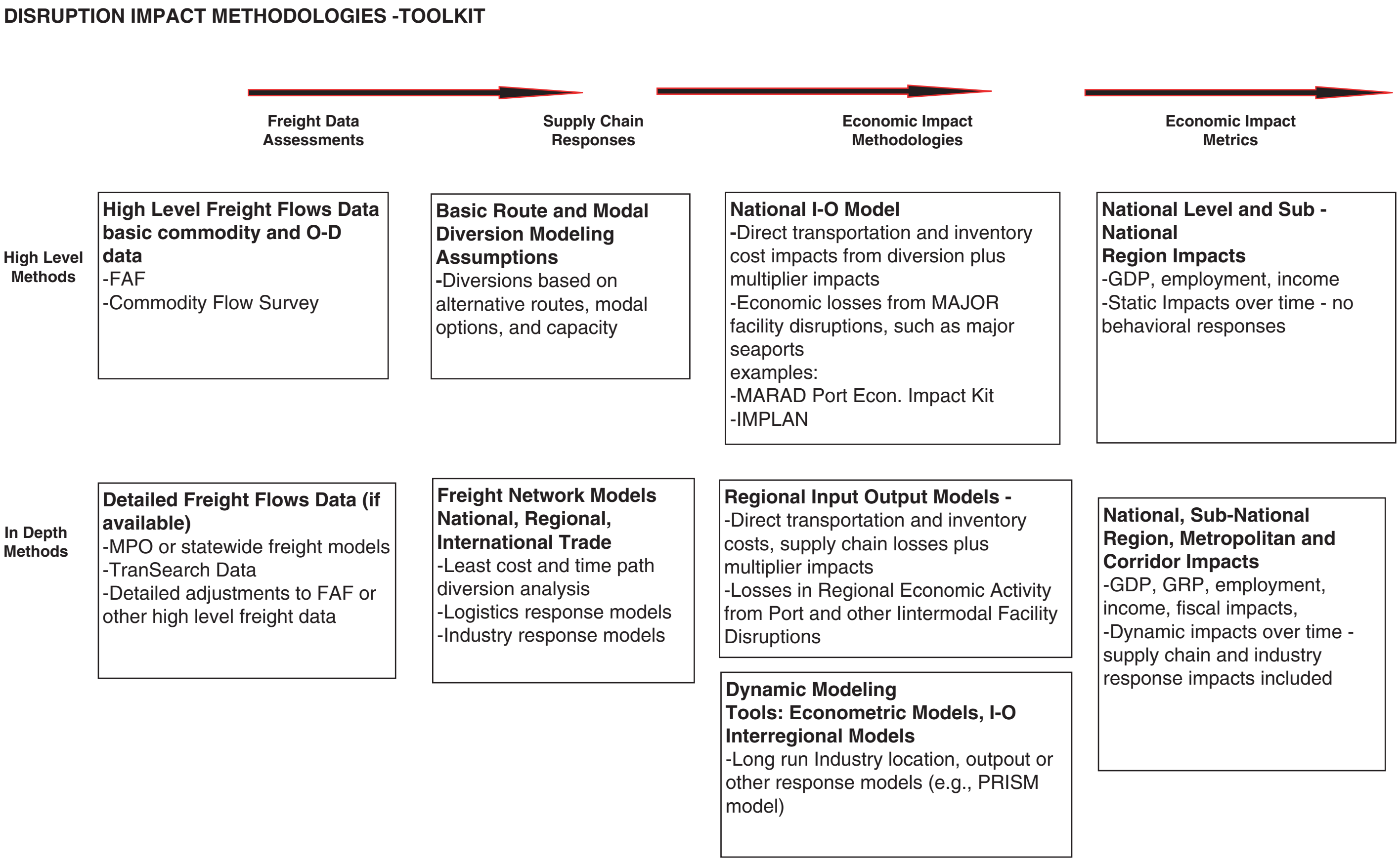


Figure 3-7. Disruption impact methodologies toolkit: high-level and in-depth methods.

increase by a given amount, we can estimate, using cost-industry output elasticities, the impacts to industry output, final sales, and from this, impacts on sales, taxes, employment, and earnings).

For the in-depth methodology, the simple approach is broadened to incorporate either freight network modeling or detailed statistical or panel studies of supply chain responses. A broad database of observed responses and data from previous surveys and literature may be assembled and could be matched to similar disruption situations. This includes any survey-based responses from impacted shippers, carriers, freight handlers and forwarders, and receivers. Detailed shipment and other supply chain handling and transaction cost data are required for pre- and post-disruption conditions, by principal cost element (freight rates, delivery time penalties, insurance rates, fuel costs, etc.). Data on inter-industrial linkages, typically in the form of inter-industry by commodity use-and-make tables, is needed to capture indirect impacts. The economic impacts would then be expanded in the in-depth methodology to use more sophisticated economic analysis tools and models, including I-O-based tools and general equilibrium economic impact models that typically involve an econometric or statistically calibrated component. For long-distance, inter-regional impacts, the FHWA's national commodity flow database (the FAF) will need further disaggregation down to county, or perhaps even lower, levels of spatial resolution. No standard method currently exists, although there have been a number of recent efforts to do so (see Southworth 2009), while others are ongoing (e.g., NCFRP 20). IHS Global Insight's Transearch database (see http://www.ihs.com/products/global-insight/industry-analysis/commerce-transport/database.aspx) offers a popular proprietary county-level multiple commodity flows matrix. However, at the time of this writing, all such matrices must rely on a combination of shipper and carrier survey plus secondary data sources (e.g., county or zip code area population and economic activity reporting) and a number of flow modeling assumptions.

Modeling Possibilities

The possibilities are organized into the following three groups of costs or impacts.

1. Social and public sector costs
   - Changes (increases or decreases) in network maintenance costs, based on net regional, mode-specific VMT changes
     - Changes from traffic rerouting will have little impact on overall routine highway maintenance costs since regional VMT will not change much, but there can be a transfer of impacts from one location. or possibly from one state to another, in cases of widespread diversion incidence
     - Changes are more significant where there are modal diversions and truck volumes fall significantly across the entire network
   - Increased network congestion on undamaged facilities
     - Crude estimates can be based on additional VMT under congested conditions and based on diversion assumptions or actual diversion analysis, using sources such as the Texas Transportation Annual Mobility Report
     - Within a travel demand model where additional levels of link congestion can be estimated and measured using metrics such as VMT or VHT under congested conditions (LOS D,E,F)
2. Changes in externalities, such as emissions, based on net regional changes in mode-specific vehicle miles of travel
     - These impacts may also need to be weighted to reflect increased overall levels of congestion from truck reroutings (i.e., if volumes are diverted from LOS C facilities to other facilities, which then operate under LOS F) emissions and congestion costs would both experience net increases
3. Direct supply chain costs
   - Increased direct truck transport costs from diversion, based on vehicle mile and vehicle hour changes
     - Given truck VMT and VHT changes, trucking cost factors can be readily obtained from numerous benefit-cost analysis studies and sources
   - Increased inventory carrying costs, calculated based on changes in ton hours by commodity type, value of the commodity, and assumed time value of money (inventory costs)
     - Increased direct truck transport costs from diversion can lead to increased inventory costs calculated based on changes in ton hours by commodity type, value of the commodity, and assumed time value of money (inventory costs); the DIETT Model, for example, includes algorithms and look-up tables for this
     - Possible increases in costs due to investments made in maintaining more resilient (more flexible, with more redundancy) supply chains.

Assumptions may also need to be made about the share of shipper costs borne by/passed on to the carrier or to beneficial owners of cargo (BFOs). Assessments should also reflect net regional impacts, such as potential increases in local trucking activity in some areas at the expense of other areas (i.e., potentially no net change in costs or benefits, but a change in the spatial distribution of impacts). Measures include producer and consumer surplus.

Inter-Industry and General Equilibrium Impacts

These are industry impacts due to increased transport costs and time, reduced reliability, reduced supply chain efficiency, increased warehousing, and other supply chain modifications. This analysis may include both direct and indirect impacts due to the effects on firms' abilities to satisfy final demands for their products and services. I-O modeling is the most common approach to use here (not necessarily using the complete U.S. framework). More elaborate inter-regional and iteratively designed general equilibrium models may be useful for more detailed studies over protracted periods of time. Metrics include changes in employment, income, value added, business income, and gross regional product. The ability to model industry-specific impacts is limited by the extent to which commodity-specific flows and transport plus other transaction cost increases can be estimated in Step 3 above. Considerations include the following:

- Direct industry impacts represent that share of the overall transport cost increase borne by each industry sector (e.g., manufacturers, big box retailers, agricultural and other raw materials producers, and transportation, warehousing, and distribution service providers). Increases reflect increased transportation costs and increased inventory costs, which combined result in increased overall logistics costs, reduced reliability that can be monetized, supply chain inefficiencies, loss of JIT capabilities, etc.
- Increased transport and supply chain costs are described above in Step 3, but further modeling can be applied, such as via the PRISM regional economic impact model, to derive, not just direct, but also indirect and induced impacts due to the effects on firms' outputs and abilities to satisfy final demands for their products and services. PRISM utilizes an I-O model (IMPLAN) to estimate these, combined with assumptions and information specific to each industry/commodity impacted.
- Metrics include changes in employment, income, value added, business income (lost sales), and gross regional product.
- The ability to model industry-specific impacts is limited by the extent to which commodity and NAICS-specific freight flows and transport cost increases can be estimated in Step 3 above.
- Assumptions can be made about the extent to which increases in transport and other logistics costs (due to diversions, more road time, more VMT, and increased overtime hours) are passed forward to shippers versus absorbed by the trucking companies and operators. Both producers and other consumers of freight transport, as well as the freight transport providers themselves (i.e., the truckers), are sectors within the economy, and each sector can be treated differently in terms of inter-industry impacts. For some major firms, those providing in-house transportation, costs are a direct impact to the businesses.
- Potentially useful models include PRISM, TREDIS, REMI, and IMPLAN, which model the static inter-industry relationship structure via I-O models and, in some cases such as REMI, are more general equilibrium models.
- Simplified I-O-based models are more suitable for the high-level methodology in estimating the unit changes in economic impact due to changes in the transportation system. REMI or similar GE models are less suitable for a high-level methodology due to very high implementation costs and complexity of modeling approaches.

CHAPTER 4

Case Studies

4.1 Introduction

Case studies were conducted to apply the concepts identified in the economic impact analysis methodology presented in Figure 3-1. The case studies encompass different freight modes, including rail, highway, ports, maritime, and inland waterways, and cover impacts at the local, regional, and national scales. Table 4-1 presents a number of disruption events, the principal modes of transportation impacted by each event, and the geographic extent (local, regional, national) of the economic impacts resulting from disruptions to the freight transportation network. The shaded cells indicate cases that were chosen for analysis.

The cases were selected to provide an opportunity to study in some depth the various supply chain responses to disruptions and to generalize these findings to the extent possible in order to develop rules of thumb that can be used to estimate economic impacts within the high-level methodology.

Although a number of the cases had impacts at all levels, all but one of the case studies was intended to focus on the economic impacts at a specific geographic scale. Thus, for example, although the impacts of 9/11 were felt both regionally and nationally, New York City experienced severe disruptions within its local freight transportation network, providing an opportunity to look at disruptions to the enormous volume of intra-regional truck deliveries that are the lifeline of the New York City economy. In contrast, the Los Angeles/Long Beach Port disruption was included in order to demonstrate the differences in the scope, magnitude, and incidence of economic impacts when viewed from a local, regional, and national perspective.

4.2 The Northridge Earthquake, Southern California, 1994

Step 1: Define the Direct Freight Transportation Network Impacts

Nature of the Disruption

On January 17, 1994, a magnitude 6.8 earthquake centered on the Northridge community in the San Fernando Valley caused widespread damage to buildings, gas supply lines, and four freeways in the Los Angeles area of Southern California.

Transportation Facilities and Services Impacted

The highway network to the north and west of the Los Angeles central business district suffered a number of bridge collapses and other severe structural damage. In particular, the highway interchange between I-5 (the Golden Gate Freeway) and State Route (SR)-14 collapsed. I-5 is the principal north-south truck route through the region. East-west traffic was also impacted. The I-10 (Santa Monica Freeway) bridges at Fairfax Avenue and Washington Boulevard collapsed;

Table 4-1. Major disruption events and their modal and geographic contexts.

		Economic Consequences to be Examined		
Disruption	Mode(s)	National	Regional	Local
Iceland Volcano	Air Cargo	X		
2011 Japan Earthquake	Shipping	X		
I-40 Bridge Collapse	Barge, Trucking	X		
Hurricane Katrina	Rail, Trucking	X	X	
I-5 Floods (WA)	Trucking	X	X	
Baltimore Rail Tunnel Fire	Rail	X		
LA/Long Beach Port Closure	Shipping, Trucking, Rail	X	X	X
"9/11"	Trucking		X	X
Minneapolis Bridge Collapse	Trucking		X	X
Northridge Earthquake	Trucking		X	X

X = Case Study

and major damage also occurred to the Gothic Avenue and Bull Creek bridges in the western San Fernando Valley along SR-118 (see Figure 4-1).

Modes Impacted

The event disrupted highway travel, including the movement of significant volumes of truck freight traffic.

Timeframe of the Disruption

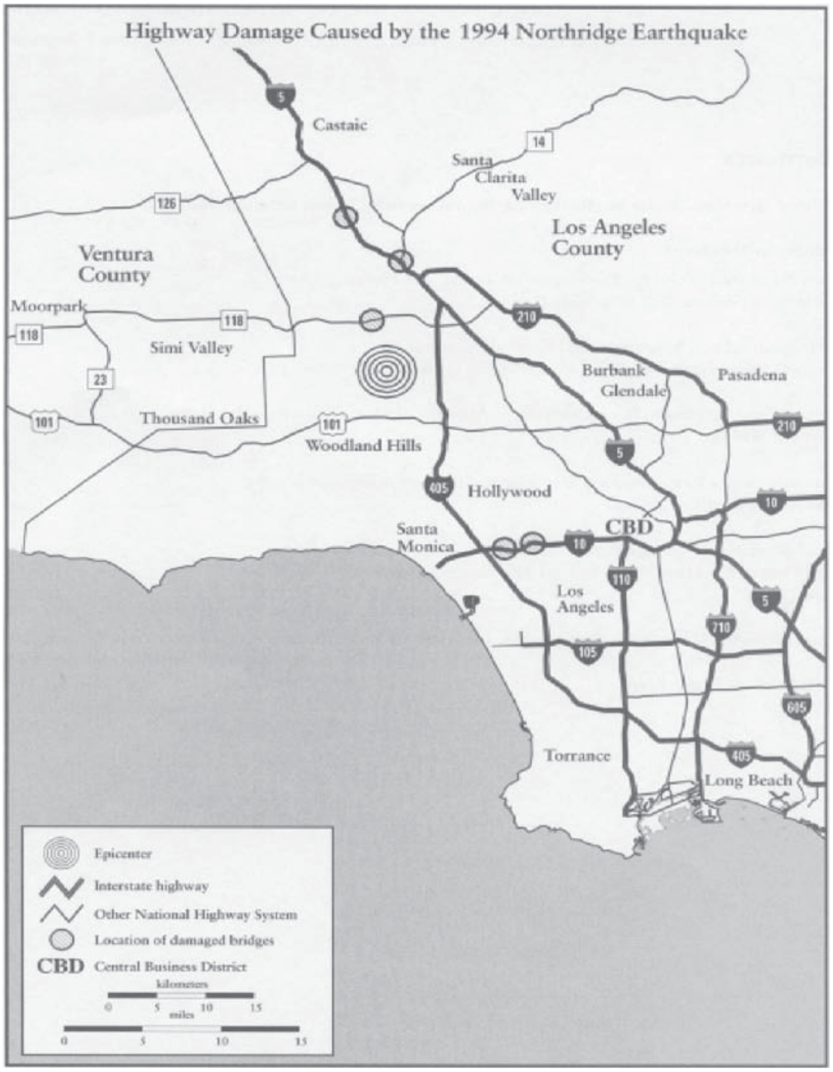
The highways were repaired within a few months of the disaster. On May 17 and 18, 4 months after the earthquake, I-5 through lanes were reopened. On July 8, less than 6 months after the earthquake occurred, the I-5/SR-14 interchange lanes were reopened, and the last connector ramps within the junction were reopened in November (Giuliano and Golob 1998; Wesemann et al. 1996).

Step 2: Identify Current and Future Affected Network Flows by Facility and Link

The I-5, I-10, SR-118, and SR-14 freeways all lost traffic due to closure. Parallel routes and local connectors in a five-county area were impacted and operated under congested conditions for a period lasting from 4 to 6 months.

Traffic Flows During the Network Reconstruction Period

The junction of I-5 and SR-14 is a complex set of mainline and connector lanes designed to accommodate large total traffic volumes and heavy truck traffic in very steep terrain. Also due to the terrain, there are few arterials in this area. The California Department of Transportation (Caltrans) estimated the pre-earthquake corridor freeway traffic volume at around 260,000



Source: *Journal of Transportation and Statistics,* Vol 1.2, May 1998.

Figure 4-1. Northridge earthquake—highway damage sites.

vehicles per day. The traffic on the affected section of I-5 dropped 59 percent immediately due to lack of alternative routes (Zhu and Levinson 2008). According to Wesemann et al. (1996), traffic count data showed significant loss of traffic on I-5 leading up to the damaged section of highway, with the SR-14 truck bypass lanes, which offered a primary detour option, accepting 75 percent to 80 percent of the pre-quake trips.

Arterial streets in the vicinity of the damaged I-5 and SR-14 interchange also experienced significantly higher traffic volumes during reconstruction, carrying as many as 30,000 vehicles (autos and trucks) per day more than they did before the earthquake occurred. A drop in traffic volumes on the order of 6 percent occurred. Long-haul regional truck traffic used to I-5 was significantly impacted by the network closures. Both Caltrans traffic counts and responses to a May 1994 truck intercept survey indicated that truck traffic dropped some 30 percent, with rerouted traffic having to travel significant additional distances in order to use alternative regional highway corridors such as I-15 and US-101 (Wesemann et al. 1996).

During highway reconstruction, the traffic volumes on the affected section of the eight-lane I-10 freeway dropped from some 310,000 to around 130,000 vehicles (average annual daily traffic) based on counts taken about 10 weeks into the recovery, with significant increases in parallel arterial street volumes in the vicinity of the damaged roadway. An Automated Traffic Surveillance and Control (ATSAC) system operated by the City of Los Angeles made it possible to improve throughput on these arterials through real-time signal adjustments. The detour included two designated alternate routes, with a shorter detour reserved for HOVs, while other traffic was diverted off the freeway for a longer distance and onto more distant arterials. On-street parking was removed from the detour arterials, providing additional travel lanes. Medians were restriped to provide additional turning lanes at key intersections, and signal timing was adjusted to favor through traffic. The Freeway Service Patrol (a roving emergency response service) was expanded to cover the detour arterials. Extensive signage guided travelers along the detour routes. With minor modifications, the detour remained in operation until the freeway reopened on April 12 (Giuliano and Golob 1998). A drop in mixed traffic volumes on the order of 13 percent is estimated to have occurred during the reconstruction period (Wesemann et al., 1996). A limited number of travelers shifted to bus travel during the reconstruction phase, while ridership on Metrolink rail transit lines rose quickly at first then gradually declined back to pre-event levels as more throughput capacity was returned to the freeway corridors (Giuliano and Golob 1998).

Traffic Flows after Re-Opening of the Freeways

After restoring 70 percent of pre-earthquake capacity along I-5 by implementing a series of mitigation projects, traffic volumes increased to 88 percent of pre-earthquake levels. After full capacity was restored in May 1994, total traffic increased quickly and went beyond the 1993 level in June by 1 percent. Once the detour had been completed, by the end of January, daily truck volumes on I-5 and SR-14 soon returned to near normal levels. Similarly rapid returns to pre-disruption traffic volumes occurred in the I-10 and SR-118 corridors.

Step 3: Define Supply Chain Characteristics and Parameters by Flow Type

The network disruptions caused by the earthquake were limited to the highway network and hence affected the costs of trucking materials into, out of, within, and through the Southern California region. Where delays in delivery times occurred, these could add further logistics costs at the pick-up and receiving ends of a shipment, whether from/to local customers or from/to the region's large seaports. Based on a post-event survey of businesses in the region, Gordon et al. (1998) reported that 11.2 percent of responding firms suffered from commuting interruptions, 4.2 percent from inhibited customer access, 7.4 percent from shipping disruption, and 4.6 percent from interrupted supplies. The limited duration of the event, with partial throughput capacity restored in a matter of 3 months and with alternative routes quickly upgraded and made available to truckers, suggests that most economic costs directly associated with the transportation network were trucking industry-related.

Step 4: Supply Chain Response Modeling

Based on survey data, most responses to the disruption by trucking firms were short term in nature, including (see Willson 1998, Table 6):

- Rerouting (81 percent),
- Rescheduling (69 percent),
- Increases in driver overtime (55 percent),
- Reductions in the frequency of deliveries/pick-ups (38 percent), and
- Consolidation of loads (29 percent).

There was little use of alternative transportation modes (rail or air modes). The principal response was rerouting, especially among courier firms. Responding firms said that most (96 percent) of these actions were no longer being used by mid-May of 1994 (Willson 1998). Some 14.3 percent of firms surveyed said they changed their shipping practices, while 6.6 percent indicated that they had altered their supply arrangements since the network disruption (Gordon et al. 1998).

Step 5: Economic Impact Modeling

Timeframe

The post-recovery reports available for this event suggest that the economic impacts were of a short-run nature, on the order of 6 months to a year, with the majority of costs associated with the diversion of trucks to much longer routes and to temporary increases in operational costs associated with logistics activities such as the need to consolidate less-than-truck-load (LTL) shipments and increases in truck driver overtime. No major modal shifts occurred, and no lasting changes in industry supply chains, such as changes in the location of product sourcing or changes in product markets, appear to have taken place.

Spatial Considerations

The major economic impacts appear to have occurred within the state and mainly within the southern California region, mostly in the form of localized shifts in trucking activity. Most of the trucking firms impacted made intra-regional deliveries within Southern California. However, business losses were spread much more widely. According to Gordon et al. (1998), of over $6.5 billion in lost business, 51 percent occurred within the immediate impact zone, most of it (47.7 percent) in direct economic costs. Some 15.8 percent of losses were sustained outside the Southern California region, including abroad. This implies some, if comparatively small, effects also on oceanic shipping and domestic rail shipments into and out of Southern California via the ports of Los Angeles and Long Beach.

Direct Supply Chain Costs

Wesemann et al. (1996) provide estimates of daily area-wide truck travel delay costs during reconstruction, broken down by delays on the I-5, I-10, and SR-14 freeways, on parallel arterial streets, and due to regional reroutings. These totaled 7,832 hours of daily delay, associated with some 63,000 daily truck trips. Evaluated at $19.20 per hour this is equal to $155,000 in trucking delay-related costs per day, as well as some $10,000 per day in excess truck fuel used due to additional en route congestion (as derived from data in Tables 2 and 4 of Wesemann et al. 1996). A post-event survey of firms in the region reported by Boarnet (1998) also indicated that transportation network damage played an important role in the business losses that occurred following the earthquake, with 43 percent of the responding firms indicating that some portion of their business losses was due to transportation damage, attributing some 39 percent of their losses directly to transportation service disruptions. When asked a series of questions about the biggest problems they faced as a result of the earthquake, the top four responses were all related to transportation system disruptions, in the form of customer and employee access to the business location and shipping delays to and from the worksite.

Inter-Industry and General Equilibrium Impacts

Gordon et al. (1996, 1998) used post-event survey data and an I-O model to estimate business losses in terms of lost person-years of industrial-sector-specific employment, which they translated into an estimated $6.5 billion loss of economic output, of which just over $1.5 billion is attributed to transportation service disruptions. Of this $1.5 billion dollars, almost $731 million was attributed to commuting time losses, with the rest assigned to business logistics issues. In round figures, the authors attributed costs associated with restrictions on customer access to $272 million ($229 million within the 5-county Southern California region), costs associated with shipping problems to over $484 million ($408 million within the region), and costs due to supply disruptions at $299 million ($252 million within the region).

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4.3 Winter-Storm-Related Closures of I-5 and I-90 in Washington State, 2007–2008

Step 1: Define the Direct Freight Transport Network Impacts

Nature of the Disruption

In December 2007, heavy rainfall west of I-5 in the Willapa Hills, combined with melting snow from the mountains, created extremely high floodwaters in western Washington State. Twenty-four-hour rainfall intensities were 140 percent higher than the 100-year amounts for areas in Southwest Washington. High winds, heavy rains, mudslides, and falling trees made travel unsafe on highways across much of the western part of the state. Downed power lines blocked roads and, in many urban areas, rainwater overwhelmed drainage systems and water pooled on roadways. Dozens of residents were trapped by mudslides, some needing to be lifted to safety by U.S. Coast Guard helicopters.

Transportation Facilities and Services Impacted

A 20-mile section of I-5 near Cherhalis in western Washington was flooded and closed for 4 days, with 12 feet of flowing water on I-5 in some places. Flooding and a massive landslide at Mile Post 27 and various other smaller slides and flood debris also caused SR 6 between Centralia/Chehalis and Raymond/Hoquiam/Aberdeen to be closed both ways to all traffic from December 3 through December 29, 2007. In addition to the disruptions to highway traffic, the Curtis Industrial Park rail line and eight culverts, which connected the Port of Chehalis to the Curtis Industrial Park near Pe Ell, also experienced flood damages. The Chehalis-Centralia airport levee failed and water covered most of the airport during the 4 days of flooding along I-5. A section of I-90 through Snoqualmie Pass was closed for 4 days in February 2008 due to the threat of weather-induced heavy snowfall and avalanches.

Modes Impacted

Highway (truck) traffic along Interstates 5 and 90 were affected.

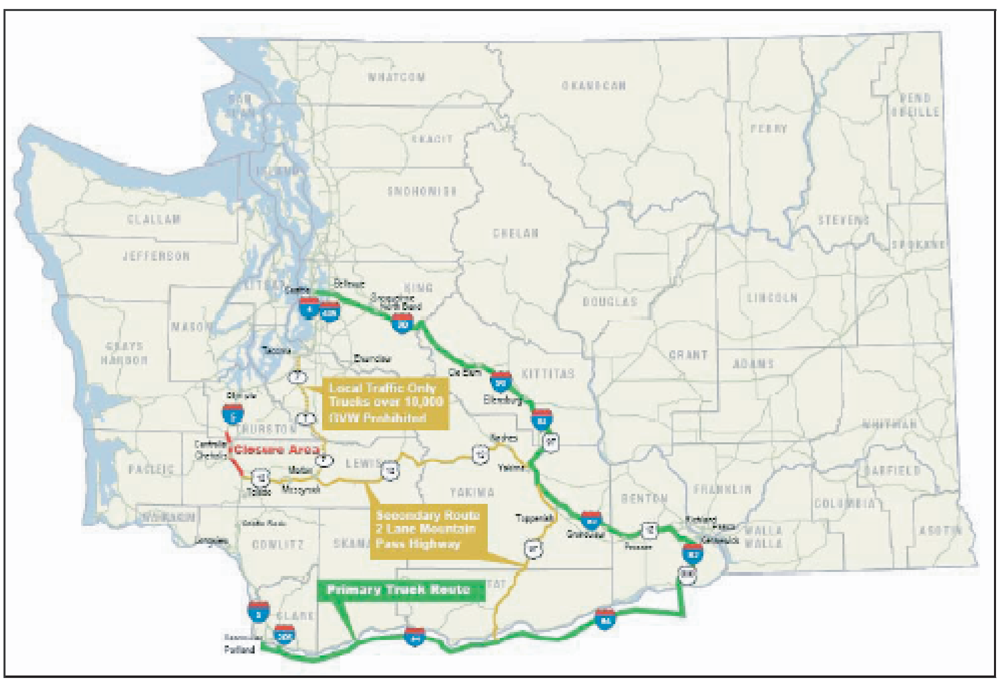
Timeframe of Disruption

I-5 was closed for 4 consecutive days from December 3 through the morning of December 7 of 2007, with some limited capacity to handle heavier trucks late on December 6th. Beginning in late January, less than 2 months after the Chehalis area flooding closed I-5, the state experienced another major highway system disruption. Record snowfall and warm temperatures in the mountain passes created snowfall and avalanche threats that closed I-90 at Snoqualmie Pass for 89 hours from January 29 through February 2, 2008.

Step 2: Identify Current and Future Affected Network Flows by Facility and Link

Traffic Flows during the Network Reconstruction Period

Prior to the flood damage, more than 54,000 vehicles traveled the affected stretch of I-5 daily, including almost 10,000 trucks. Washington State DOT (WSDOT) responded to the closure by providing e-mail updates to freight companies on the agency's listserv and by frequently updating WSDOT's Website with the most current information on detour routes and road conditions. These updates provided companies and truckers with the best information available, enabling them to plan and strategize as much as possible. WSDOT also established several detour routes through southern Washington and Oregon (see Figure 4-2). Working with the Washington State Patrol and local communities, the state DOT also allowed trucks carrying emergency supplies and extremely perishable goods for local communities to use the nearby State Route 7, a much shorter alternate route (an extra 85 miles), on a case-by-case basis. Lack of capacity and safety issues, as well as noise and road damage, caused WSDOT to prevent trucks from using this route otherwise, based on prior experience with flooding in 1996. As shown in Figure 4-2, WSDOT established a primary truck detour along I-84 in Oregon and on I-82 and I-90 in Washington. This route added 440 miles and some 8.5 hours of driving to an otherwise approximately 200-mile trip from Portland to Seattle. (By the third day of the closure, trucking companies were at risk



Source: *WSDOT,* 2008.

Figure 4-2. I-5 closure detour map.

Source: *WSDOT,* 2008.

Figure 4-3. I-90 pass closure detour map.

of losing drivers due to federally mandated Hours of Service regulations, which require truck drivers to take a 10-hour rest period after 11 hours of driving.) Many trucks instead chose to take U.S. Route 97, which still added some 344 additional miles to the trip (WSDOT 2008, page 5).

The closure of I-90 was similarly problematic. On a typical weekday, approximately 6,500 trucks travel over I-90 at Snoqualmie Pass. With most of the state's east-west routes closed due to very heavy snowfalls, trucks were left with very few options. WSDOT's recommended detour routes (see Figure 4-3) called for trucks to detour southward along I-82 to I-84 in Oregon. Severe weather also caused a closure of I-84 between Pendleton and La Grande for a time, cutting off all east-west detour routes. Highway 12 over White Pass also had to be closed for avalanche control and to clear accidents.

Traffic Flows after Re-Opening of the Interstates

No detailed, post-flooding assessments of traffic flows were undertaken. This is probably because truck traffic movements returned to normal soon after the interstate routes were reopened, as might be expected along routes whose pavements were not damaged sufficiently to prevent traffic from moving over them once the high water or snowfall had been removed from the road surface.

Step 3: Define Supply Chain Characteristics and Parameters by Flow Type

The network disruptions caused by the flooding and heavy snowfall were limited to the highway network and hence affected the costs of trucking materials into, out of, within, and through Washington State. Where delays in delivery times occurred, these could add further logistics costs at the pick-up and receiving ends of a shipment.

Step 4: Supply Chain Response Modeling

According to the WSDOT economic impact analysis of the closures: "As a practical matter, there are no substitute routes to effectively transit I-5. The interstate is the West Coast's major north-south corridor for both freight and auto traffic" and "I-90 is the longest Interstate highway in the United States, stretching from Seattle to Boston. It is the main highway route for east-west commerce in the state linking Puget Sound to Spokane in eastern Washington. The route connects eastern Washington agriculture businesses and other industries with urban markets in northwest Washington and Puget Sound, along with global markets via the Ports of Seattle and Tacoma." (Ivanov, Hammond, and Reinmuth 2008).

Step 5: Economic Impact Modeling

Timeframe

The post-recovery reports available for this event suggest that the economic impacts were limited to a few months.

Spatial Considerations

The major economic impacts appear to have occurred to businesses along the closed routes, but also with impacts on both north-south (I-5) and east-west (I-90) semitrailer and triple-trailer truck traffic carrying goods to/from Washington State seaports for both within and outside the state.

Direct Supply Chain Costs

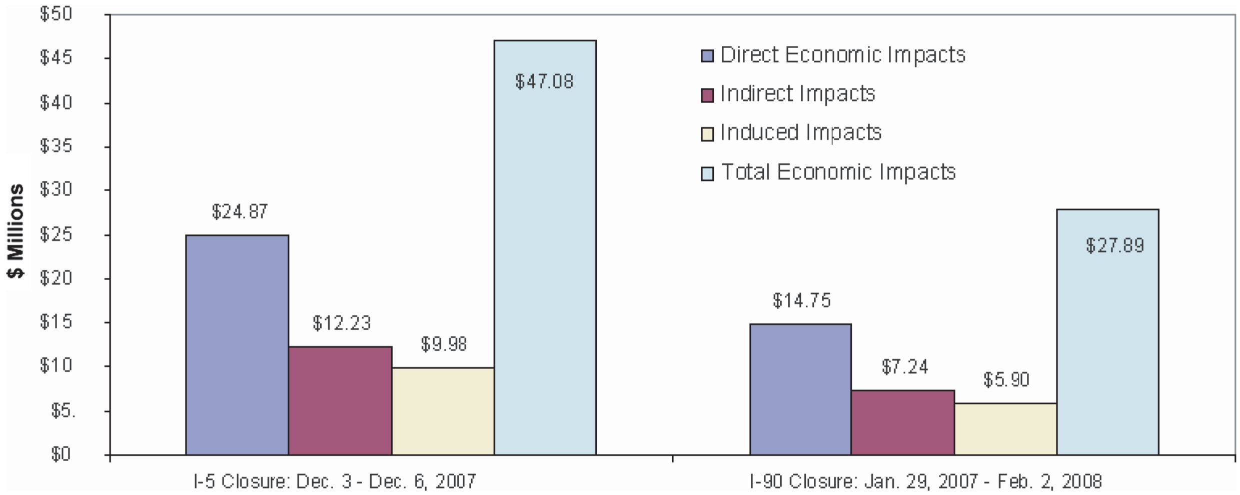
A WSDOT study of the total economic impact of these two weather-induced network disruptions to the state's freight systems estimated combined costs at almost $75 million, of which some $47 million was associated with the I-5 disruption (Ivanov, Hammond, and Reinmuth 2008). The analysis was based on a survey that obtained responses from 2,758 affected trucking firms and freight-dependent businesses statewide and included queries about the following:

- Revenue losses (losses incurred by firms that could not deliver products for their customers in time, including losses associated with perishable goods and losses incurred because firms did not receive the orders their customers had placed);
- Additional business costs incurred by both the trucking industry and freight-dependent sectors (costs associated with delays, detours, and use of alternative modes of delivery, and other actions, which caused additional costs. Such costs encompass increased fuel charges, increased wages and overtime pay for drivers, additional communication costs, higher costs of using alternative methods for delivery of goods, and other operational costs). Trucking companies reported that the I-5 detours took a substantial toll on their businesses, requiring double the resources—including drivers, power units, and trailers—to make the longer trips—The additional cost of taking the detours was estimated to be between $500 and $850 per truckload; and
- Future disruption prevention costs (i.e., costs that firms planned to expend in order to prevent additional future losses and to ensure retention of customers).

Inter-Industry and General Equilibrium Impacts

Estimation of the above listed direct impacts on the economic output of the trucking industry and freight-dependent sectors was subsequently expanded to include any indirect and induced economic impacts (as well as impacts on output, employment, personal income, and state tax receipts) using the IMPLAN-based Washington State input-output economic model. The state was estimated to have lost over $3.8 million in tax revenues, and 460 jobs (WSDOT 2008; Ivanov, Hammond, and Reinmuth 2008).

Figure 4-4 shows the results of this analysis broken down by the two network disruption events. The $37.1 million in direct business losses attributed to the two highway closures combined were themselves constructed from three sources: losses in business sales (58 percent), additional freight costs such as fuel and overtime pay for drivers (39 percent), and future loss prevention costs reported as being taken by the freight carriers interviewed (about 3 percent). The analysis



Source: WSU/WSDOT Economic Impact Survey of I-5 and I-90 Winter Storm Closures, 2008.

Figure 4-4. Impacts on economic output due to the I-5 and I-90 winter storm closures (in $ millions).

also broke down its economic impact estimates for the trucking industry and freight-dependent sectors within each of the state's seven major geographical regions, noting similar impact across all regions other than the coastal region, where the I-5 closure impacts were noticeably more severe. The study also provides some interesting qualitative business firm specific case study reports. The state's trucking industry, which depends on the state's primary freight corridors for daily business, suffered the highest percentage of lost revenues. Trucking companies reported losing 0.51 percent of their total annual revenue because of the two highway closures. The state's freight-dependent sectors reported an average loss of 0.05 percent of their total annual sales revenue, while freight-dependent companies that operated their own truck fleets lost 0.32 percent of their total revenues. All other economic sectors lost approximately 0.01 percent of the year's sales revenues, a very small percentage, but multiplied by a large annual revenue number.

In addition to the above estimated business losses, estimated highway damage from the winter storm was $18 million for state routes and another $39 million for city and county roads.

Case Study References

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4.4 Local Impacts of the 9/11 World Trade Center Attack

Step 1: Define the Direct Freight Transport Network Impacts

Nature of the Disruption

The events of September 11, 2001, are succinctly summarized in a report published by the Organisation for Economic Co-operation and Development (OECD 2002) as follows:

> On the morning of Tuesday, 11 September 2001, the United States was hit by a set of unprecedented terrorist attacks, calculated to inflict massive civilian casualties and damage. Four hijacked commercial jets crashed, two into the World Trade Center towers in Manhattan, which collapsed shortly thereafter, one on the Pentagon in Washington D.C., and the last one in Pennsylvania.

A September 27, 2002, *Report for Congress* on the subject starts with, "The tragedy of September 11, 2001, was so sudden and devastating that it may be difficult at this point in time to write dispassionately and objectively about its effects on the U.S. economy" (Makinen 2002). More time has passed and, while the emotions associated with the event remain, many assessments have been made regarding the impacts. The focus of this case study is the impact of the attacks on the supply chain and, more specifically, on the movement of goods in the New York-New Jersey region.

Step 2: Identify Current and Future Affected Network Flows by Facility and Link

Transportation Facilities and Services Impacted

The attacks immediately affected all aspects of the U.S. supply chain—roadways were closed, rail service slowed, and ports and airports were closed. Border traffic was halted, as follows:

> Immediately after the attack, the U.S. Customs Service moved to Alert Level One, which called for intensive anti-terrorism operations at all borders and points of entry. The U.S.-Mexico and U.S.-Canada borders were closed entirely . . . Railroads faced speed and service restrictions in the northeast United States immediately after the attacks . . . Out of all modes of transportation, airlines were the most adversely affected. All commercial air service was shut down, airports were emptied, and the Federal Aviation Administration (FAA) prohibited passenger planes from carrying cargo (Lee and Hancock 2005). Ports throughout the United States were immediately shut down.

Step 3: Define Supply Chain Characteristics and Parameters by Flow Type

Short-Term Impact on Supply Chain

- On September 11, the U.S. Coast Guard shut down the port. However, recovery moved swiftly—by the afternoon of September 12, a plan to reopen the port was developed. On September 13, vessels began leaving the Port of New York and New Jersey. The port was fully opened and functioning on September 14.
- All airports and U.S. air space were closed immediately after the attacks. An article noted, "A week after the attacks, most airlines were offering full services again, and the ban by FAA was lifted. The only contingency on carrying international cargo was that it had to be off-loaded at the first U.S. city at which the plane arrived, where it then had to be moved to its final destination by surface transportation." (Lee and Hancock, p. 9) New York officials noted that airport operations resumed in waves and that John F. Kennedy International Airport (JFK) was also affected by road closures in the New York City area. These conditions resulted in shippers and forwarders trying alternative airports and having to think differently about their air cargo movements.
- The bridges and tunnels between New York and New Jersey were similarly affected by the attack. The Holland Tunnel, located closest to Ground Zero, was most affected and was closed for the longest period of time. Utility work was required to return basic functionality. The tunnel was also needed to remove debris from Ground Zero and for response efforts. New York City, at the time, had limited all traffic to the lower Manhattan area.

Step 4: Supply Chain Response Modeling

Even with the significant damage and closures, New York businesses and residents continued to be served. Supplies and equipment to ramp-up alternative office facilities were quickly brought in. Response vehicles, construction equipment, and debris removal occurred.

Assessments of the impact of 9/11 on the supply chain conclude that the greatest disruptions to the supply chain appeared to have resulted from the border closures. "The severe tightening of border controls following the September attacks resulted in long waiting times that disrupted the operations of manufacturing companies, especially at the U.S.-Canada border" (OECD 2002).

Industries that had adopted just-in-time inventory strategies appeared to have been most affected. Lee and Hancock summarize the impact on the automotive industry as follows:

> Auto production was halted at more than 60 plants in the United States and Canada on 9/11 as manufacturers were unable to get critical inventory . . . Ford closed all Canadian and U.S. manufacturing facilities, as did DaimlerChrysler Corp., Toyota Motor Manufacturing, and Mitsubishi Motor Manufacturing. Ford cut production 13 percent the week following the attacks because of blocked parts delivery and still ended up losing more than 16,000 units of production by the end of that same week. General Motors initially lost about 100 total hours of production at eight plants—six in the United States and two in Canada—and a week after the attacks reported 10,000 lost units of production (Bryce 2001). BMW reported 750 units of production were lost when it ceased production at its Spartanburg, South Carolina, plant, and Toyota and Honda had to shut down plants for a few days after the attacks. All automakers with North American facilities were affected, resulting in an estimated 52,636 units of production lost in the first week (Ward's Auto World, 2001).

The impacts on the New York-New Jersey roadways were related primarily to the rerouting of traffic. Many food services and JFK-bound trucks had used the Holland Tunnel, which was closed to truck traffic from September 11, 2001, until January 2011. Reduced access to JFK was a challenge for many trying to use the airport.

Permissible truck heights at the Holland and Lincoln Tunnels were restricted prior to 9/11. It was noted during the interviews that prior to 9/11, the Port Authority was already considering restrictions at its tunnels for trucks larger than straight trucks for safety reasons—the tunnel had 10-foot lanes and sharp curves—and to be able to accommodate industry standard buses at the facilities.

The overall impact on supply chain thinking is summarized in the following quote:

> The events of September 11, 2001, brought significant attention to several questions and motivated the need to think beyond lean and be able to deal with major supply chain disruptions. Before 9/11, supply chain security meant preventing things from being ***removed*** from the logistics cycle by unauthorized parties. In the post-9/11 world, concern has also focused on preventing disruptive elements from being ***inserted*** into supply chain operations to create violent havoc. Today we ask: How do we reduce the impact of new security initiatives on supply chain and freight transportation network productivity and how can we design competitively productive supply chains that exhibit "resiliency" (i.e., degrade gracefully and recover quickly) when a major disruption occurs? (White 2010)

Resiliency considerations are now more often considered in both public- and private-sector planning, both for freight and passenger transportation.

Step 5: Economic Impact Modeling

The longer term impacts appear to be most related to discretionary cargo markets, implementation of post-9/11 security initiatives, and resiliency in the supply chain. JFK, according to Port Authority officials, lost air cargo traffic because some shippers and forwarders stayed with the alternative routings explored immediately after 9/11. JFK had historically been used for international air cargo movements for a large portion of the North American market. By being forced to try alternative gateways and finding these alternatives better for serving certain markets, shippers and forwarders changed their long-held practices. JFK, the New York-New Jersey region's predominant international airport, lost business and is working hard to regain market share.

The Port of New York and New Jersey was not affected in the long term. All ports were equally affected; vessels had no place to go. The quick reopening of ports led to a resumption of maritime traffic along pre-9/11 lines. It was noted by port officials that the 2002 West Coast Port Strike had a much greater impact on ports—in the aftermath of the strike, major shippers adopted a "port diversification" policy. Instead of relying on a single port, shippers increased the number of ports used so as not to be affected in the future by such region-specific disruptions.

However, the significant changes and enhancements in seaport and airport security have required the shippers, terminal operators, agencies, and transportation providers to make equally significant investments in security equipment and personnel. Enhancements include perimeter fencing, new worker background checks and identification cards, radiation detectors, and scanning of cargo. Much has been written regarding the implications of enhanced security on the supply chain. However, it has also been noted that the enhanced security efforts also helped address long-standing theft issues.

Case Study References

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4.5 Los Angeles/Long Beach (LA/LB) Ports Shutdown, California, 2002

Step 1: Define the Direct Freight Transportation Network Impacts

Nature of the Disruption

In 2002, the labor contract between the International Longshoremen and Warehouse Union (ILWU) and the Pacific Maritime Authority (PMA) was expiring and came up for negotiation. The negotiations stalled, resulting in a work slowdown. The PMA responded by imposing lockouts of dock workers in September and October (Farris 2008). Given that this potential disruption was being played out in a public way, shippers and carriers could have anticipated the actual event, thus making this case study different than the others. Also, the importance of the Ports of LA/LB in the global supply chain was such that any shutdown of these ports would likely reverberate throughout the world.

Transportation Facilities and Services Impacted

The Ports of LA/LB together represent one of the largest container port terminals in the world. The twin ports account for 32 percent of U.S. imports and 17 percent of exports (Park et al. 2002). Due to their size and importance, the impact of the shutdown spread nationally. Thus, not only were the port facilities and the surrounding support services affected, but the regional highway system, national railroads, and the corresponding highway/rail facilities serving those ports now receiving freight diverted from the LA basin were also affected.

Modes Impacted

The event disrupted cargo container transportation by water, rail, and highway.

Timeframe of the Disruption

The work slowdown and the lockouts spanned a period of several weeks starting mid-September 2002. On October 9, 2002, President Bush ordered the workers back to work by invoking the

Taft-Hartley Act. However, ILWU members continued their systematic work slowdown and PMA reported a significant productivity decline. The slowdown ended in late November 2002, when PMA and ILWU reached an agreement (Farris 2008).

Step 2: Identify Current and Future Affected Network Flows by Facility and Link

Traffic Flows During the Network Disruption Period

The Ports of LA/LB together rank as the sixth largest container port in the world. Together with Oakland, Seattle, Tacoma, and Portland, the six largest West Coast container ports handled 253 million tons of cargo and were responsible for more than half of all foreign containers passing through U.S. ports in 2001. The total worth was just over $300 billion, or 42 percent of waterborne trade in the United States (Farris 2008).

Figures 4-5 and 4-6 show the before, during (Point 3), and after exports and imports for LA, San Francisco, and others, including San Diego, Columbia-Snake, and Seattle (Park et al. 2002). When President Bush stepped in on October 9, over 200 ships had lined up outside of the Ports of Los Angeles and Long Beach. It was estimated that it would take 6 to 7 weeks to clear this backlog. The backlog had grown to over 100 days by the time the contract between PMA and ILWU had been settled (Farris 2008).

Traffic Flows after Re-Opening the Ports

Figures 4-5 and 4-6 show that vessel imports and exports were restored to the pre-shutdown days quickly after the labor dispute was resolved. Cargo volume hit record levels after the new contract was signed and, in 2003, coast-wide container throughput was up 10 percent (Farris 2008).

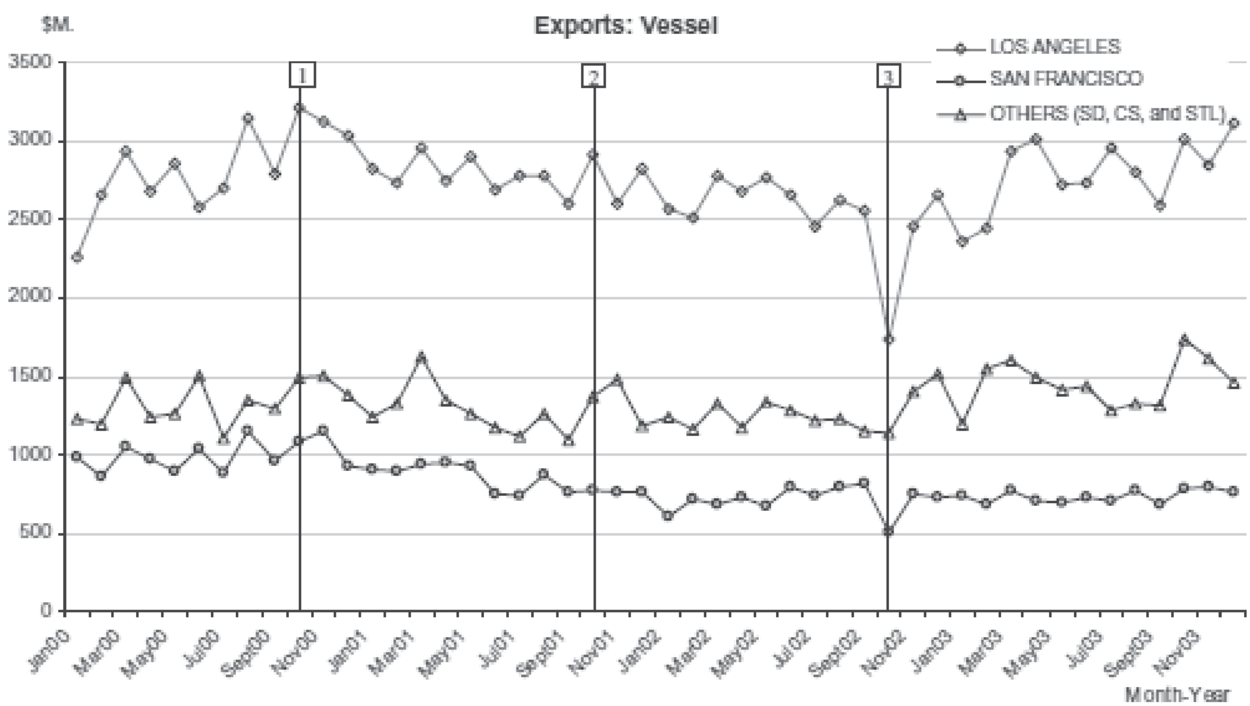

Figure 4-5. Foreign exports for vessel mode by customs district (Park et al. 2002).

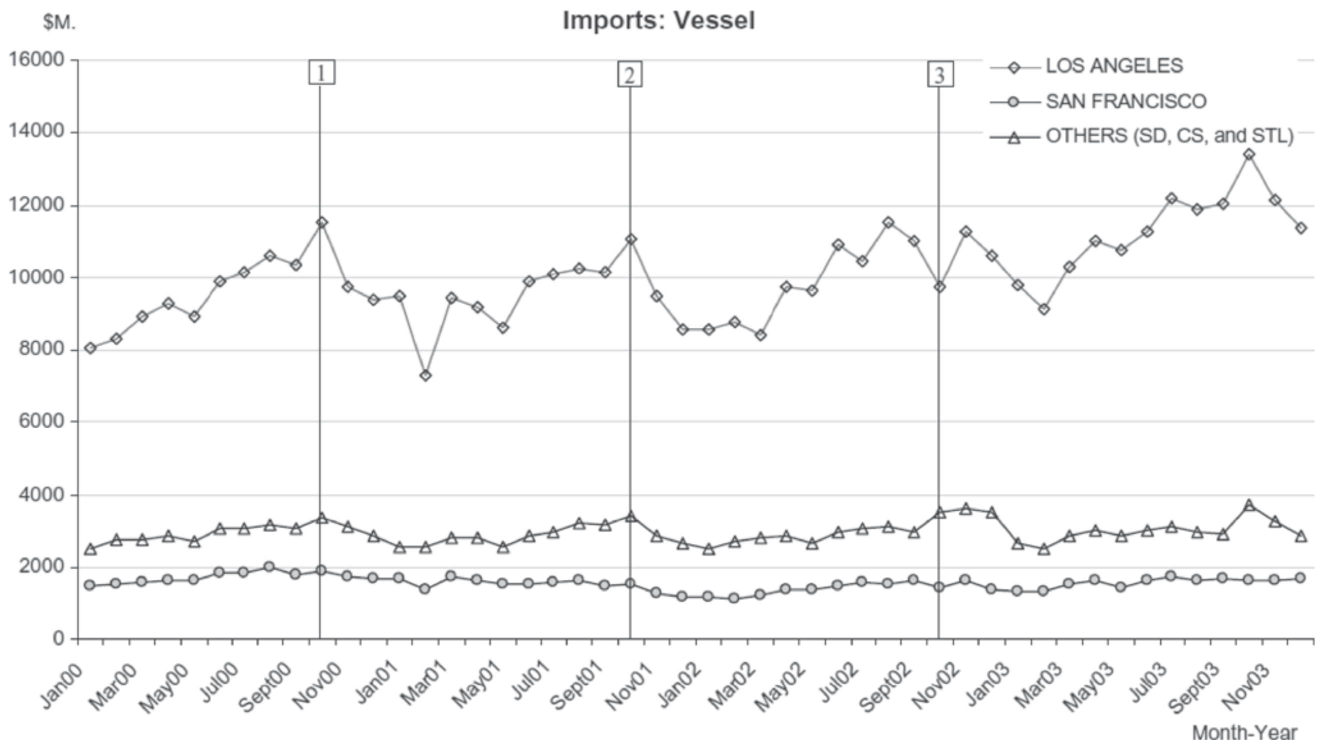

Figure 4-6. Foreign imports for vessel mode by customs district (Park et al. 2002).

Step 3: Define Supply Chain Characteristics and Parameters by Flow Type

The port shutdown not only affected maritime traffic, but also had a spillover effect with respect to other modes. Truckers were unable to return containers to the port terminals or to pick up new cargo, railroads lost shipping business to and from ports, and air cargo saw a slight increase. In addition, due to the size and importance of the ports, not only was the state of California affected, but so were all coastal states in the West, as well as neighboring states and even the nation as a whole. The key variables with respect to the short-term supply chain response was the associated economic cost to the shippers and carriers that waited out the shutdown, or the additional costs associated with diverting traffic to other ports. For example, some carriers with cargo destined for the East Coast diverted ships through the Panama Canal to East Coast and Gulf ports. The Port of Savannah, Georgia, for example, experienced substantial growth in container movements during the shutdown and immediately after.

Step 4: Supply Chain Response Modeling

Although many vessels awaited clearance for the port, the major response to the incident in traffic terms was rerouting of vessels to other ports and the rescheduling of vessels. Park et al. (2002) indicated that there was a positive impact on port trade along the West Coast before the shutdown (due to the anticipation of some disruption) and that during the shutdown only LA and San Francisco experienced a negative impact, while other ports experienced growth. Shippers were trying to find other ports of entry in a way that satisfied supply chain constraints while minimizing costs. Park et al. (2002) also found that there were modest positive impacts on air cargo.

Burlington Northern and Santa Fe Railways lost their container business serving the ports (normally 4,000–7,000 units per day) during the shutdown, but claimed that much of that traffic was either shipped before or after the shutdown, resulting in minimal loss overall (Zuckerman 2002).

In the longer term, there is some evidence to suggest that shippers and carriers viewed the port shutdown as an opportunity to re-examine their dependence on the ports for satisfying supply chain needs. For example, some carriers seriously examined the possibility of moving containers via the Suez Canal to eastern ports and, in fact, such services have been instituted (although it is not clear that they were done in direct response to the port shutdown). With the widening and deepening of the Panama Canal, it is likely that many shippers and carriers will be examining the use of the all-water route to the East Coast of the United States, primarily due to cost considerations, but in some cases, it is likely that dependence on a major port facility for satisfying supply chain movements (and the vulnerability associated with it) also is under consideration.

Step 5: Economic Impact Modeling

Timeframe

The post-recovery reports of this event suggest that the economic impacts were limited to a few months, although they were significant to some in the supply chain. The majority of costs were associated with cargo delays and the temporary increases in operational costs associated with logistics activities. No major modal shifts have occurred, and no lasting changes in industry supply chains, such as changes in the location of product sourcing or changes in product markets, appear to have taken place in any significant way, although the experience of the shutdown does seem to have influenced carrier and shipper thinking about the vulnerability of the supply chain with respect to the port.

Spatial Considerations

The major economic impacts appear to have occurred within the coastal states in the West (both positive and negative), as well as selected East Coast ports and in the nation as a whole. The ports export (and to a lesser degree import) products that come from all over the United States.

Direct Supply Chain Costs

Several studies have analyzed the economic impact of the port shutdown with varying results. Initial estimates indicated an economic cost to the U.S. economy of $1 billion per day. Martin Associates conducted a study for the Pacific Maritime Association and estimated the total cost to be $21.4 billion, or $1.94 billion per day for the 11 days. They later adjusted that number to $15.6 billion ($1.42 billion per day) after having interviewed over 200 operators, carriers, importers, exporters, etc. According to Martin Associates, $14.4 billion was lost by exporters and importers (Farris 2008). This $1–2 billion per day range was quickly adopted by the media, the maritime industry, and politicians. Other studies and several major newspapers, however, imply that this figure was an exaggeration. Anderson (2002) estimated that the total cost to the U.S. economy caused by the ports shutdown was only $1.67 billion, or $140 million per day. His estimates were based on his conclusion that while some food items may have spoiled, most cargo was simply delayed, not canceled.

Hall (2004) criticized the method used by Martin Associates. He stated that while this method is useful for analyzing economic effects of cargo handling at ports and docks, there are many short-comings with respect to a broader economic impact study. Short-comings include a limited short-term substitution behavior analysis (rerouting to other ports, changing production strategies, etc.) and the exclusion of both winners and losers of a disruption. Haveman and Shatz

(2006) point out that the lockout saw a significant (short-term) decrease in imports and exports at the Ports of LA/LB, but that the total imports at the national level only decreased by a few percentage points. Park et al. (2002) included rerouting, rescheduling, alternate modes, and "winners" in their analysis, and they concluded that the import-related economic impact was positive ($579 million) over a total of 5 months during and after the shutdown, while the economic losses for exports were $3 billion during those 5 months.

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4.6 The I-40 Arkansas River Bridge Collapse near Webbers Falls, Oklahoma, May 2002

Step 1: Define the Direct Freight Transportation Network Impacts

Nature of the Disruption

On May 26, 2002, the captain of the tugboat *Robert Y. Love* experienced a blackout that caused him to lose control of the vessel. As a result, the barge he was controlling collided with a bridge support, causing a 580-foot section of the I-40 bridge over the Arkansas River to collapse into the water (see Figure 4-7). Several automobiles and tractor trailers fell from the bridge, resulting in 14 deaths.

Source: FHWA (2002).

Figure 4-7. I-40 bridge collapse in 2002. See http://xpda.com/i40bridge/for additional aerial pictures.

Transportation Facilities and Services Impacted

I-40 traffic had to be rerouted through local roads, and Arkansas River barge traffic on the McClellan-Kerr Arkansas River Navigation System into and out of Tulsa's Port of Catoosa was stopped for about 2 weeks (Pant et al. 2011). The highway rebuilding cost was about $30 million, in part because of repairs to the alternate routes.

Modes Impacted

The event disrupted both highway and barge traffic through the region, including the movement of significant volumes of truck freight.

Timeframe of the Disruption

The I-40 highway bridge was re-opened to traffic on July 29, 2002, 65 days after the disaster occurred.

Step 2: Identify Current and Future Affected Network Flows by Facility and Link

Traffic Flows during the Network Reconstruction Period

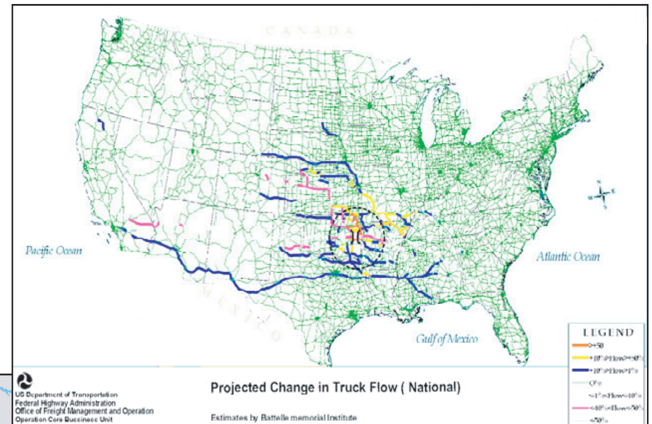
The I-40 bridge is on a major east-west transportation corridor connecting Memphis, Tennessee; Oklahoma City, Oklahoma; and Albuquerque, New Mexico. Prior to its collapse, the 1,988-foot-long, four-lane bridge carried an estimated 22,000 vehicles per day. During the 2-month closure, an estimated 20,000 vehicles per day had to be rerouted over other paths on the highway system (see Figure 4-8). This included an estimated 6,000 to 7,000 trucks. Eastbound delays were expected to be about 45 to 50 minutes while westbound traffic was expected to be delayed 15 to 20 minutes.

Traffic Flows after Reopening of the Bridge

Very little analysis of post-recovery traffic volumes has been conducted. Truck traffic appears to have returned to its pre-collapse routes soon after the bridge was reopened. Some barge traffic was able to move through the main navigable channel during the bridge reconstruction and appears to have returned to normal volumes soon after the incident. As Figures 4-9 and 4-10 show, the effects on port throughput, at least in total tonnage terms, appears to have been short lived.

Step 3: Define Supply Chain Characteristics and Parameters by Flow Type

Highway (truck) traffic was disrupted significantly by the bridge collapse. Simulation studies of the potential highway networkwide impacts of the bridge collapse were carried out by Oak Ridge National Laboratory and Battelle Memorial Institute (see FHWA 2002 and Figure 4-8) and also, more recently, by the Oklahoma Universities Transportation Center (Ingalls et al. 2009). Although the largest impact on truck movement volumes was on alternative routes in close proximity to the collapse site, both studies found that a significant number of trucks using I-40 originated, or were destined for, locations outside Oklahoma, with subsequent impacts on route-specific truck traffic volumes outside the immediate vicinity of the accident (see Table 4-2). Figures 4-11 and 4-12 show the types and volumes of commodity flows impacted.



Source: Estimates by Oak Ridge National Laboratory (Regional flows) and Battelle memorial Institute (National flows) for the FHWA Office of Operations Technical Services (FHWA, 2002)

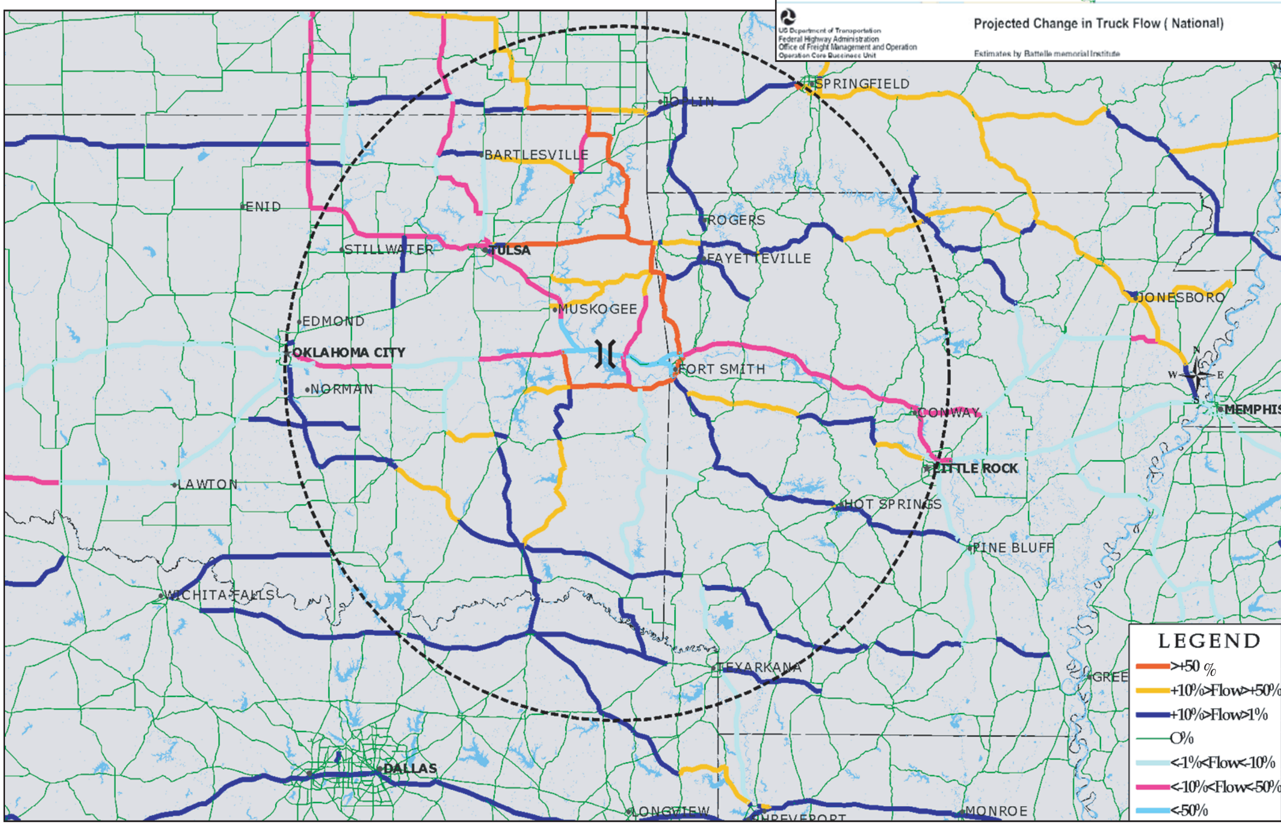
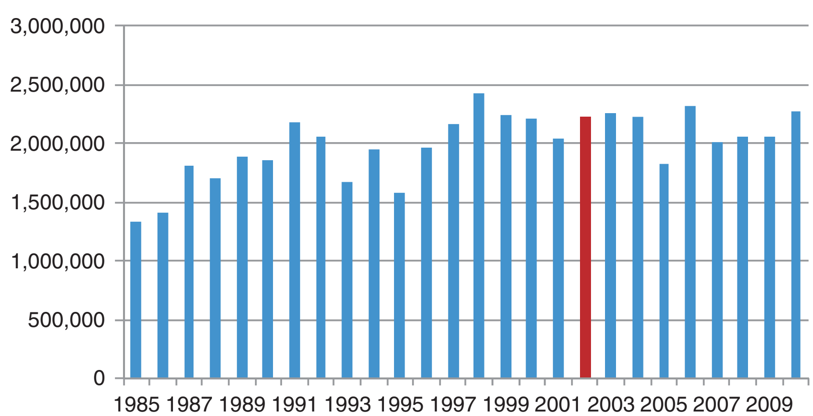
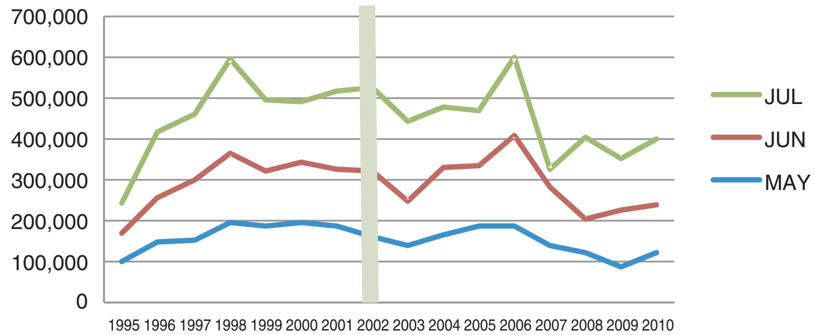


Figure 4-8. Projected percentage change in national and regional truck flows due to I-40 bridge collapse.



Source: Tulsa Port of Catoosa, http://www.tulsaport.com/about_our_waterway.html

Figure 4-9. Annual tonnages through Tulsa Port of Catoosa, 1985–2010.



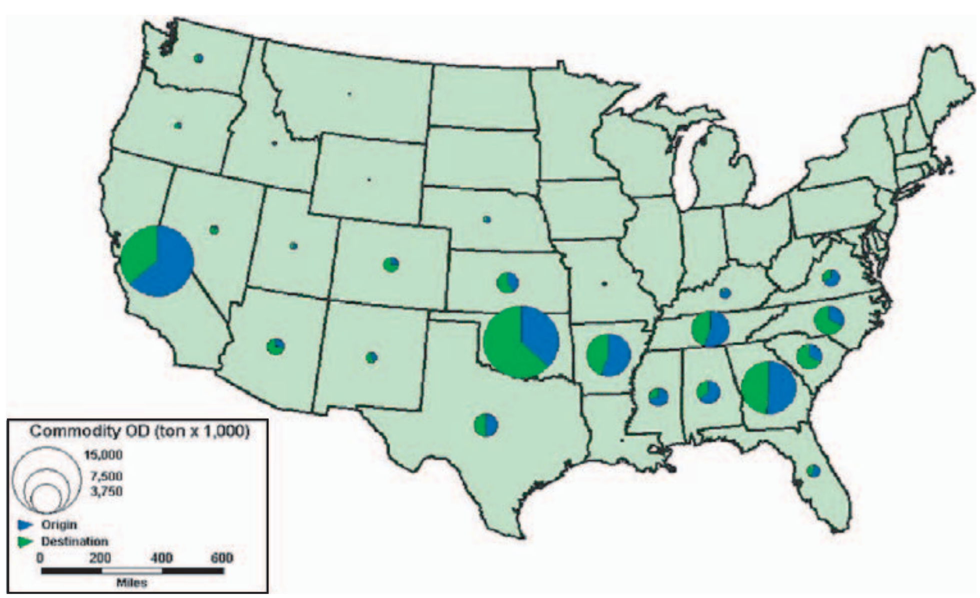
Source: Tulsa Port of Catoosa, http://www.tulsaport.com/about_our_waterway.html

Figure 4-10. May, June, and July tonnages through Tulsa Port of Catoosa, 1985–2010.

Table 4-2. Estimated percentages of non-local commodity tonnages: using the I-40 bridge crossing at Webbers Falls, Oklahoma.

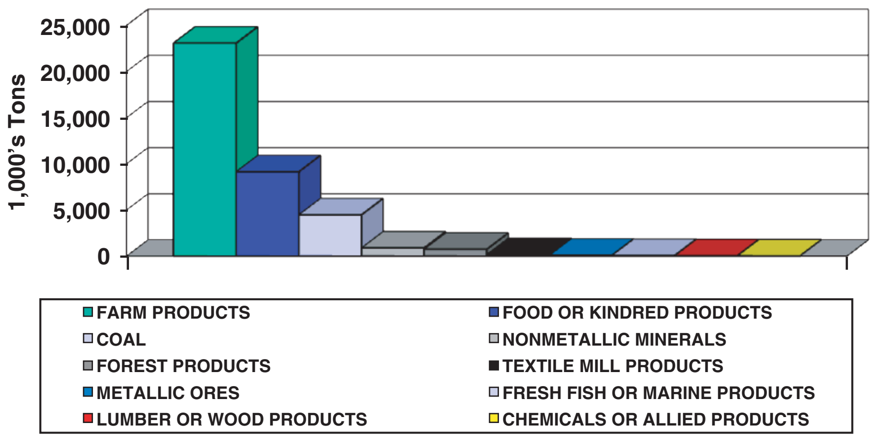
	Tons of Shipments	Value of Shipments	Assignable Truck
Within Oklahoma	8%	1%	11%
From or to Oklahoma	28%	14%	34%
Through Oklahoma	64%	85%	55%

By weight the three biggest commodity movements on I-40 through Webbers Falls are California to Georgia (4.5 million tons), Georgia to Oklahoma (4.1 million tons), and within Oklahoma (3.2 million tons).



Source: Estimates by Oak Ridge National Laboratory for the FHWA Office of Operations Technical Services (FHWA 2002).

Figure 4-11. Estimated interstate commodity flows on I-40 in 2002.



Source: Estimates by Oak Ridge National Laboratory for the FHWA Office of Operations Technical Services (FHWA 2002).

Figure 4-12. Top 10 commodities by weight crossing the I-40 bridge.

Waterway (inland barge) traffic was also disrupted for a short period of time. This included freight moving into and out of the nearby Tulsa land port of Catoosa. The following lists the main industries using the port in 2002 (Pant et al. 2011):

- Food and beverage and tobacco products
- Petroleum and coal products
- Chemical products
- Nonmetallic mineral products
- Primary metals
- Fabricated metal products
- Machinery
- Miscellaneous manufacturing

Step 4: Supply Chain Response Modeling

The major response to the incident in traffic terms was rerouting of truck volumes. Barge traffic was delayed temporarily, but appears for the most part to have awaited clearance of the navigable channel, which was open before final highway bridge reconstruction was completed.

Step 5: Economic Impact Modeling

Timeframe

The post-recovery reports available for this event suggest that the economic impacts were limited to a few months.

Spatial Considerations

The major economic impacts appear to have occurred within the coastal states in the West (both positive and negative), as well as selected East Coast ports and in the nation as a whole. The ports export (and to a lesser degree import) products that come from all over the United States.

Direct Supply Chain Costs

The Oklahoma Department of Transportation (ODOT) estimated the daily cost to traffic using the detours to be about $212,000. Much of this traffic was directed onto winding, two-lane roads through small towns. ODOT estimated that trucks would incur an additional operating cost of about $17.50 per delay hour, with eastbound delays on the order of 45 to 50 minutes and westbound delays on the order of 15 to 20 minutes.

At the Port of Catoosa, some 50 firms that relied heavily on the waterway for supplies reported losses of some $300,000 a day in revenue when the waterway was closed.

Inter-Industry and General Equilibrium Impacts

A recent study by Pant et al. (2011) used a multi-regional inoperability input-output model (MRIIM) to simulate the cascading regional economic impacts of a 2-week closure of the Port of Catoosa, similar to the closure resulting from the I-40 bridge collapse. Catoosa is the largest land port in the United States, with some 2.2 million tons of freight received and moved by the port annually. Approximately 70 companies use the port, which covers a land area of approximately 2,500 acres and provides employment in one form or another for some 4,000 people (Tulsa Port of Catoosa 2011). The authors combined data on annual, monthly, and average daily arrival tonnages from a number of sources, including the 2007 U.S. Commodity Flow Survey, the U.S. Army Corps of Engineers, and the port itself to estimate daily commodity-specific import and export volumes. They used this data in a discrete time event queuing model to simulate the supply chain characteristics associated with moving cargo through the land port over the course of a full year, under normal conditions versus a year containing the 2-week cargo supply conditions. This involved running 1,000 different simulations both with and without the network disruption event, and each involving the estimated time delays and costs associated with cargo arrivals, temporary storage, crane assisted to/from vessel transfers, and departures.

The simulation modeling, using an input-output model for 10 states and 62 industrial sectors, concluded that "the closure of the Port of Catoosa for 2 weeks causes losses to the industries that do commerce through it and is considerably cascaded to other interdependent industries that are not using the port" (Pant et al. 2011, p. 732). Direct industry demand losses were estimated at $48.6 million across all states impacted, with additional indirect output losses of $101.9 million.

Case Study References

FHWA (2002). *Commodity Flows Affected by the I-40 Bridge Collapse at Webbers Falls, Oklahoma: A Preliminary Assessment* (Draft). Federal Highway Administration, Washington, D.C., May 29.

Ingalls, R. C., et al. (2009). *Freight Movement Model Development for Oklahoma.* Report prepared for the Oklahoma Department of Transportation by the Oklahoma Transportation Center.

Pant, R., et al. (2011). Interdependent Impacts of Inoperability at Multi-Modal Transportation Container Terminals. *Transportation Research Part E-47:* 722–737.

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4.7 CSX Howard Street Tunnel Fire in Baltimore, Maryland

Step 1: Define the Direct Freight Transportation Network Impacts

Nature of the Disruption

On July 18, 2001, at about 3 P.M., an eastbound CSX freight train derailed while traveling through the Howard Street Tunnel in downtown Baltimore, Maryland (NTSB 2008, p. 1). The train, consisting of 60 cars and 3 locomotives, carried a mix of freight and hazardous materials (DHS 2001, p. 9). According to the NTSB report, 11 cars derailed, 4 of which contained hazardous materials—a tank car containing tripropylene, 2 tank cars with hydrochloric acid, and 1 tank car containing a plasticizer considered an environmentally hazardous substance. The tank car containing the tripropylene was punctured and the escaping tripropylene ignited. The fire, according to the NTSB, spread to several adjacent cars.

Source: *Baltimore Sun* as shown in ITS Program Office report, Effects of Catastrophic Events on Transportation System Management and Operations: Baltimore, MD – Howard Street Tunnel Fire – July 18, 2001, p. 8.

Figure 4-13. Howard Street Tunnel fire.

The result was a fire within the tunnel that lasted 5 days (Figure 4-13). The fire also resulted in a 40-inch water main break above the tunnel, disruptions to transit operations in Baltimore, the movement of freight to the Port of Baltimore, and Internet and telecommunications services due to damage to a cable running in the tunnel. The incident began during the evening rush hour in downtown Baltimore before a baseball game was to be played at Camden Yards. Public sirens were sounded and the Coast Guard closed the Inner Harbor. The intensity and location of the fire made it difficult to fight.

On July 23, the incident commander declared the scene under control and authorized access to the tunnel without breathing apparatus for qualified personnel. According to CSX, the train derailment caused no structural damage to the tunnel. According to the FRA *Report to Congress* (2005, pp. 2–18), "the first freight train passed through the tunnel at 8:48 A.M. on July 24, 2001."

No lives were lost. The NTSB report noted five minor injuries to firefighters (Figure 4-14).

Source: U.S. Department of Homeland Security, U.S. Fire Administration/ Technical Report Series, CSX Tunnel Fire: Baltimore Maryland, USFA-TR-140/ July 2001, p. 26.

Figure 4-14. Inspecting damage in the Howard Street Tunnel.

Step 2: Identify Current and Future Affected Network Flows by Facility and Link

The Howard Street Tunnel is owned by CSX and used solely for the railroad's freight trains. CSX describes the route as a "merchandise corridor"—predominately carload traffic, with some coal, some intermodal, and some auto traffic. It was a merchandise train that derailed and caught fire.

The tunnel, according to the U.S. Fire Administration (USFA) report, was built over a 5-year period between 1890 and 1895. The one-track tunnel is nearly 2 miles long. The USFA analysis notes that while the tunnel was little used for several decades, it is now the longest active underground train route on the East Coast, handling 40 CSX rail freight trains daily—Currently, the tunnel, rarely seen by residents, facilitates the passage of tons of freight, everything from orange juice to automobiles, fine goods, and coal (DHS 2001, p. 4).

Step 3: Define Supply Chain Characteristics and Parameters by Flow Type

The tunnel is not used for passenger service nor does it serve other rail lines. The route is one of only two national Class I rail lines that runs from the Northeastern U.S. to the Southeastern U.S. The second line is operated by the Norfolk Southern (NS). The fire effectively severed one of these two major routes. In addition, access to the Port of Baltimore was hampered due to road closures.

Step 4: Supply Chain Response Modeling

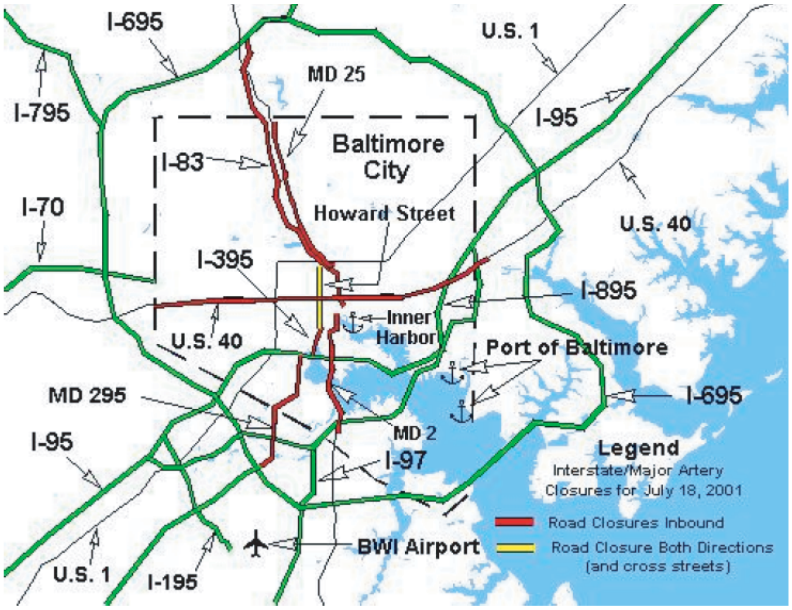
According to CSX, the railroad rerouted traffic using alternative rail freight routings, rather than using passenger lines. The railroad made it a priority to notify businesses regarding changes and conditions affecting their shipments.

The disruption caused by the tunnel fire affected both local movements in Baltimore and rail freight movements along the East Coast. Rail traffic was delayed or rerouted as far west as Ohio. The FRA report summarized the rail freight impacts as follows:

> To avoid the Howard Street Tunnel, CSX had to send freight trains west to Cleveland, Ohio, north to Albany, New York, and then south to Baltimore, incurring a 3- to 4-day delay. Some CSX trains were rerouted via the busy NS line through Manassas, Virginia, Hagerstown, Maryland, and Harrisburg, Pennsylvania. At one point during the fire, eight CSX trains that would have used the tunnel were detouring through Cumberland, Massachusetts, and Youngstown, Ohio; five through Hagerstown and Harrisburg; five through Cleveland and Albany; and 12 trains were stopping in various yards (FRA 2005, p. 2–18).

A 2002 report issued on the fire by the U.S. Department of Transportation ITS Joint Program Office noted the following impacts on the rail freight system (U.S.DOT 2002, p. 16–18):

- CSX diverted or delayed a significant portion of the rail traffic along the Eastern Seaboard.
- The railroad issued an advisory that freight moving to and from Chicago to Baltimore and Philadelphia had been rerouted through Selkirk and South Kearny, New Jersey, with expected delays of 18 to 24 hours.
- Freight moving along the Eastern Seaboard from the Northeast to Florida and other southern states was advised to expect delays of 24 to 36 hours.
- The Tropicana "Orange Blossom Special" was among the six trains rerouted by CSX over the NS track.
- Three trains were canceled.
- Freight destined for the Port of Baltimore was held either across the harbor from its destination or detoured via Philadelphia. The report notes that when the tunnel was reopened on July 24, much of the initial traffic consisted of crosstown traffic.



Source: U.S.DOT (2002).

Figure 4-15. Road closures in Baltimore due to Howard Street tunnel fire.

While the predominant impact was on the rail freight system on a multi-state level, the fire caused disruptions to businesses and surface transportation activities in the Baltimore area. The ITS Program Office report noted that, "The closing of Howard Street and the surrounding area in essence cut Baltimore's central business district in half, closing off east-west traffic flows" (see Figure 4-15).

The FRA report noted, "The fire and burst water main damaged power cables and left 1,200 Baltimore buildings without electricity. Severed fiber-optic lines backed up traffic regionally and nationally because the fiber-optic cable through the tunnel is a major line for the extremely busy Northeast corridor" (FRA 2005, pp. 2–18).

Step 5: Economic Impact Modeling

CSX indicated that there was no long-term impact on businesses because of the nature of the commodities being moved. The railroad noted that merchandise rail freight shipments are less time sensitive; the choice of rail is primarily based on cost rather than service profiles. It should be noted that the Tropicana train rerouted over NS track is an example of a more time-sensitive shipment. The train carries temperature-controlled Tropicana consumer products.

Although the disruption may not have directly affected movements over the long term, the incident did lead to considerable discussions involving the movement and routing of hazardous materials, along with tank car designs and incident management. The USFA report noted, "The train derailment in Baltimore focused attention once again on the issue of transporting hazardous material, including radioactive and nuclear waste, through densely populated areas" (DHS 2001, p.10). Testifying before Congress in October of 2001, the Mayor of Baltimore noted, "One of the first things we realized—based on our experience in the CSX tunnel fire—was that rail yards and tracks, filled with chemical tankers and munitions cars, represent one of our most vulnerable targets" (DHS 2001, p. 22).

CSX also worked to manage reputational damage. The railroad sent claims personnel out immediately. The USFA report noted the following:

> With the cause of the derailment still under investigation, CSX ran a full-page advertisement in the *Baltimore Sun,* entitled "Thanks, Baltimore!" The advertisement, addressed to the citizens of Baltimore, thanked the mayor, fire chief, "the courageous professionals of the Baltimore City Fire Department," and the emergency response personnel for their "tireless efforts, leadership and professionalism" following the derailment. It also thanked the community for its patience and support (DHS 2001, p.12).

Perhaps the biggest impact of the Howard Street Tunnel fire was on the local community. The FRA report noted

> Beyond the adverse effects on railroad traffic, there was a massive effect on life and activities in downtown Baltimore. The incident forced the closing of streets and business over much of downtown for several days. Officials canceled three Baltimore Orioles game, resulting in a $5 million loss to the team. They also closed Howard Street, along with 14 other cross streets, for 5 days. A two-block stretch of Howard Street remained closed for 6 more weeks (DHS 2001, pp. 2–18).

The USFA report listed the community impacts as including the following:

- The changes in traffic routes (with roads closed or rerouted) caused rush-hour gridlock and affected the city's light rail system. Bus service was substituted.
- The train accident caused the worst congestion in cyberspace in the 3 years that a company monitoring Internet traffic had witnessed.
- The Baltimore Department of Public Works estimated that approximately 60 million gallons of the city's water supply was used to assist the fire suppression activities.

Case Study References

Federal Railroad Administration (2005). *Report to Congress: Baltimore's Railroad Network: Challenges and Alternatives,* U.S. Department of Transportation, Nov.

National Transportation Safety Board (2008). *Railroad Accident Brief,* NTSB/RAB-04/08.

U.S. Department of Homeland Security (2001). US Fire Administration/Technical Report Series, *CSX Tunnel Fire: Baltimore Maryland,* USFA-TR-140/July. Washington D.C.

U.S. Department of Transportation, ITS Joint Program Office (2002). *Effects of Catastrophic Events on Transportation System Management and Operations: Baltimore, MD—Howard Street Tunnel Fire—July 18, 2001,* July. Washington D.C.

CHAPTER 5

High-Level Methodology

5.1 Overview of High-Level Methodology

The following discussion and methodology template (Table 5-1) describe a high-level methodology that can be applied by transportation officials to estimate the economic impacts of transportation system disruption. The purpose of the high-level methodology is to use rules of thumb for estimating the economic costs associated with different components of a system disruption. Based on the relevant literature, case studies, and the research team's experience in freight, logistics, and economic impact analysis, it was determined that a general methodology could be developed that grouped impacts according to common characteristics and that simplified the analysis in such a way that a high proportion of the economic effects could be readily captured. At the same time, it was clearly apparent that even a high-level methodology, while involving simplification, is not necessarily "simplistic." Rather, the methodology must reflect important distinctions across a number of key variables that would determine economic outcomes and also dictate analytic methods. The high-level methodology is intended to capture the most likely general set of supply chain and economic impact outcomes.

The methodology discussion features economic impact rules of thumb (i.e., impact factors that can be applied for short-term economic impact planning). Applying these rules of thumb factors requires that key assumptions be made beforehand, as follows:

- What are the likely supply chain responses to disruptions (do shippers halt production, do they draw down inventory, or do they bid up prices for intermediate products)?
- To what extent can freight realistically be diverted to other freight routings, facilities, or modes (are there other freight routing options at reasonable cost and capacity)?
- What are the likely distances and time differentials for freight diverted to other routes or modes?

As a pre-step to applying the high-level methodology, a DOT or MPO will need to have made an appropriate set of assumptions in advance of an event occurring.

After describing the methodology, this chapter will illustrate the methodology by applying it to the Northridge earthquake case study, one of the case studies conducted as part of this study, which was presented earlier. As described in that case study, the January 1994 temblor centered in the San Fernando Valley caused major damage to a widespread area; in addition to buildings and utilities, the quake caused major damage to four freeways in Southern California and included a number of bridge and interchange collapses. Significant volumes of truck traffic were disrupted until most repairs could be completed.

Table 5-1. High-level economic evaluation methodology template:

Table 5-1A. Major inland freight disruptions (highway/bridge, Class I or short line railroad (RR), waterway &/or pipeline links) — short term impacts (<90 days).

Supply Chain Response	Geographic Scope	Economic Impact	Economic Metric	Economic Impact	Economic Metric
		Impact # 1 - Direct Shipper Cost Impacts		**Impact # 2 - Inventory Cost Increases**	
freight diverted to next nearest or least cost/time transport path/facility - same mode (e.g., highway to highway diversion)	**local/regional**	**increased in-region shipper costs** - transportation costs for in-region shipments; based on FAF data	**direct regional transportation cost increases** - apply modal cost factors to change in ton miles and hours, to in-region TM/TH increase - apply ton to truck conversion factors as needed	**inventory cost increases** - cost of increased time in transporting freight to market and/or holding freight in inventory	**time value of freight** - calculated as change in regional ton hours x cost of capital per hour for private sector
	state	**increased in-state shipper costs** - transport costs for in-state	Same as above applied to in-state TM/TH increase	Same as above for state	Same as above for state
	national	**increased U.S. shipper costs** - transport cost for total U.S.	Same as above applied to U.S. TM/TH increase	Same as above for U.S.	Same as above for U.S.
		Impact # 1 - Direct Economic Output Losses		**Impact # 2 -Indirect Economic Losses**	
freight shipments disrupted/suspended	**local/regional**	**in-region shippers suspend production/sales**: industry output reduced for duration of suspension; based on FAF data	**reduced regional output, employment, earnings and value added for industry sectors affected -** output of affected industries derived from BEA or other county or regional level data sources	**direct output losses expanded for multiplier effects -** output multipliers from RIMS or IMPLAN used to estimate total regional economic losses	**indirect and total economic losses for industry sectors affected** - total impacts are sum of direct and indirect output losses; multipliers used to derive total impacts for output, employment, earnings, value added
	state	Same as above for in-state shippers	Same as above for in-state output, employment, earnings and value added	Same as above for state	Same as above for state
	national	Same as above for all U.S. shippers	Same as above for total U.S. output, employment, earnings and value added	Same as above for U.S.	Same as above for U.S.
		Impact # 1 - Direct Shipper Cost Impacts		**Impact # 2 - Inventory Cost Increases**	
freight diverted to another mode	**local/regional**	**increased in-region shipper costs** - transportation costs for in-region shipments; based on FAF data	**direct regional transportation cost increases** - apply modal cost factors to change in ton miles and hours, to in-region TM/TH increase - apply ton to truck conversion factors as needed	**inventory cost increases** - cost of increased time in transporting freight to market and/or holding freight in inventory	**time value of freight** - calculated as change in regional ton hours x cost of capital per hour for private sector
	state	Same as above for in-state shippers	Same as above applied to in-state TM/TH increase	Same as above for state	Same as above for state
	national	Same as above for all U.S. shippers	Same as above applied to U.S. TM/TH increase	Same as above for U.S.	Same as above for U.S.

Table 5-1B. Major inland freight disruptions (highway/bridge, Class I or short line RR, waterway &/or pipeline links) — long term impacts (>120 days).

Supply Chain Response	Geographic Scope	Economic Impact	Economic Metric
		Long Term Impact # 1 - Small to Moderate Reductions in Economic Output, Employment, Earnings, GDP	
freight diverted to next nearest or least cost/time transport path/facility - same mode (e.g., highway to highway diversion)	**local/regional**	**persistent transport and inventory cost increases reduce business productivity and output** - shippers affected reduce output as a function of increased production costs	**total reduction in economic output, employment and earnings**: output elasticities applied to shipper cost increases, by industry; IMPLAN or other multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added
	state	Same as above for state	Same as above for state
	national	Same as above for U.S.	Same as above for U.S.
		Long Term Impact # 1 - Moderate to Major Reductions in Economic Output, Employment, Earnings, GDP	
freight shipments disrupted/suspended	**local/regional**	**direct loss in industry output and sales -** industry output from BEA or other data	**total reduction in economic output, employment and earnings**: output multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added
	state	Same as above for state	Same as above for state
	national	Same as above for U.S.	Same as above for U.S.
		Long Term Impact # 1 - Small to Moderate Reductions in Economic Output, Employment, Earnings, GDP	
freight diverted to another mode	**local/regional**	**persistent transport and inventory cost increases reduce business productivity and output** - shippers affected reduce output as a function of increased production costs	**total reduction in economic output, employment and earnings**: output elasticities applied to shipper cost increases, by industry; IMPLAN or other multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added
	state	Same as above for state	Same as above for state
	national	Same as above for U.S.	Same as above for U.S.

Table 5-1C. Ocean/air cargo port disruption (port out of service or major direct intermodal connections to port disrupted) — short term impacts (<90 days).

Supply Chain Response	Geographic Scope	Economic Impact	Economic Metric	Economic Impact	Economic Metric
		Impact # 1 - Direct Shipper Cost Impacts		Impact # 2 - Inventory Cost Increases	
freight diverted to next nearest or least cost US Port	**local/regional**	**increased in-region shipper costs** - transportation costs for in-region shipments; based on FAF data	**direct regional transportation cost increases** - apply truck mile and truck hour unit cost factors to in-region TM/TH increase - apply ton to truck conversion factors as needed	**inventory cost increases** - cost of increased time in transporting freight to market and/or holding freight in inventory	**time value of freight** - calculated as change in regional ton hours x cost of capital per hour for private sector
	state	Same as above for state	Same as above applied to in-state TM/TH increase	Same as above for state	Same as above for state
	national	Same as above for U.S.	Same as above applied to U.S. TM/TH increase	Same as above for U.S.	Same as above for U.S.
		Impact # 1 - Direct Shipper Cost Impacts		Impact # 2 - Inventory Cost Increases	
freight diverted to next nearest or least cost non-US Port	**local/regional**	**increased in-region shipper costs** - transportation costs for in-region shipments; based on FAF data	**direct regional transportation cost increases** - apply truck mile and truck hour unit cost factors to in-region TM/TH increase - apply ton to truck conversion factors as needed	**inventory cost increases** - cost of increased time in transporting freight to market and/or holding freight in inventory	**time value of freight** - calculated as change in regional ton hours x cost of capital per hour for private sector
	state	Same as above for state	Same as above applied to in-state TM/TH increase	Same as above for state	Same as above for state
	national	Same as above for U.S.	Same as above applied to U.S. TM/TH increase	Same as above for U.S.	Same as above for U.S.
		Impact # 1 - Direct Economic Output Losses		Impact # 2 -Indirect Economic Losses	
freight shipment disruption/suspension	**local/regional**	**in-region shippers suspend production/sales**: industry output reduced for duration of suspension; based on FAF data	**reduced regional output, employment, earnings and value added for industry sectors affected** - output of affected industries derived from BEA or other county or regional level data sources	**direct output losses expanded for multiplier effects** - output multipliers from RIMS or IMPLAN used to estimate total regional economic losses	**indirect and total economic losses for industry sectors affected** - total impacts are sum of direct and indirect output losses; multipliers used to derive total impacts for output, employment, earnings, value added
	state	**in-state shippers suspend production/sales**: industry output reduced for duration of suspension; based on FAF data	**reduced state output, employment, earnings and value added for industry sectors affected** - output of affected industries derived from BEA or other state level data sources	Same as above for state	Same as above for state
	national	**US shippers suspend production/sales**: industry output reduced for duration of suspension; based on FAF data	**reduced national output, employment, earnings and value added for industry sectors affected** - output of affected industries derived from BEA or other national data sources	Same as above for U.S.	Same as above for U.S.

Table 5-1D. Ocean/air cargo port disruption (port out of service or major direct intermodal connections to port disrupted) — long term impacts (>120 days).

Supply Chain Response	Geographic Scope	Economic Impact	Economic Metric	Economic Impact	Economic Metric	Economic Impact	Economic Metric
		Long Term Impact # 1 - Small to Moderate Reductions in Shipper Output and Secondary Economic Impacts		**Long Term Impact # 2 - Direct port losses - reduced port employment, wage earnings, GDP**		**Long Term Impact # 3 - Direct port losses - lost port revenues from shipping**	
freight diverted to next nearest or least cost US Port	**local/regional**	**persistent transport and inventory cost increases reduce business productivity and output** - shippers affected reduce output as a function of increased production costs	**employment and earnings**: output elasticities applied to shipper cost increases, by industry; IMPLAN or other multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added	**affected port worker hours reduced; local/ regional port support businesses lose sales -** estimated based on current port cost information, earlier port economic impact studies; IO-based models	**total regional output, employment, earnings and GDP reductions** - MARAD Port Economic Impact Kit or other IO-based models used to estimate multiplier effects	**cargo throughput suspended -** all in-port revenue generating activities lost for duration of disruption	**revenues loss -** estimated based on current revenues or revenue per container or per freight ton throughput
	state	Same as above for state	Same as above for state	**affected port worker hours reduced; local /regional port support businesses lose sales** - same as above only if freight diverted to out-of-state port	Same as above for state	**cargo throughput suspended -** all in-port revenue generating activities lost for duration of disruption only if freight diverted to out-of-state port	**revenues loss -** estimated based on current revenues or revenue per container or per freight ton throughput
	national	Same as above for U.S.	Same as above for U.S.	No major net national impacts where freight diverted to other US port	No major net national impact	No major net national impacts where freight diverted to other US port	No major net national impact
		Long Term Impact # 1 - Small to Moderate Reductions in Economic Output, Employment, Earnings, GDP		**Long Term Impact # 2 - Direct port losses - reduced port employment, wage earnings, GDP**		**Long Term Impact # 3 - Direct port losses - lost port revenues from shipping**	
freight diverted to next nearest or least cost non-US Port	**local/regional**	**persistent transport and inventory cost increases reduce business productivity and output** - shippers affected reduce output as a function of increased production costs	**total reduction in economic output, employment and earnings**: output elasticities applied to shipper cost increases, by industry; IMPLAN or other multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added	**Affected port worker hours reduced; local/regional port support businesses lose sales -** estimated based on current port cost information, earlier port economic impact studies; IO-based models	**Total regional output, employment, earnings and GDP reductions** - MARAD Port Economic Impact Kit or other IO-based models used to estimate multiplier effects	**Cargo throughput suspended -** all in-port revenue generating activities lost for duration of disruption	**revenues loss -** estimated based on current revenues or revenue per container or per freight ton throughput
	state	Same as above for state	Same as above for state	Same as above for state	Same as above for state	**Cargo throughput suspended -** all in-port revenue generating activities lost for duration of disruption only if freight diverted to out-of-state port	**revenues loss -** estimated based on current revenues or revenue per container or per freight ton throughput
	national	Same as above for U.S.	Same as above for U.S.	Same as above for U.S.	Same as above for U.S.	**Cargo throughput suspended -** all in-port revenue generating activities lost for duration of disruption only if freight diverted to a non-U.S. port	**revenues loss -** estimated based on current revenues or revenue per container or per freight ton throughput
		Long Term Impact # 1 - Moderate to Major Reductions in Economic Output, Employment, Earnings, GDP		**Long Term Impact # 2 - Major Impacts on Shippers from Sustained Shipment Disruptions, Inventory Depleted and Supply Chain Permanently Reorganized**			
freight shipment disruption/ suspension	**local/regional**	**Direct loss in industry output and sales as firms suspend production -** industry output from BEA or other data	**total reduction in economic output, employment and earnings**: output multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added	**Multiple Long Term Responses** - 1) Shipper firms relocate out of region or 2) Shipper firms remain, permanently shifting supply chain to next nearest port	**Lost economic output, employment, wage earnings, GDP**: In case of: 1) relocation: firm output permanently lost to region, and total regional economic activity falls; or 2) next best port permanently adopted: regional industry output falls due to higher transportation and inventory costs		
	state	Same as above for state	Same as above for state	Same as above for state	Same as above for state		
	national	Same as above for U.S.	Same as above for U.S.	Same as above for U.S.	Same as above for U.S.		

Table 5-1E. Major air cargo disruptions — short term impacts (<90 days).

Supply Chain Response	Geographic Scope	Economic Impact	Economic Metric	Economic Impact	Economic Metric
		Impact # 1 - Direct Economic Output Losses		**Impact # 2 -Indirect Economic Losses**	
air freight suspensions for affected US air cargo movements	**national**	**US shippers suspend production/sales**: industry output reduced for duration of suspension	**reduced state output, employment, earnings and value added for industry sectors affected -** output of affected industries derived from BEA or other state-level data sources	**direct output losses expanded for multiplier effects -** output multipliers from RIMS or IMPLAN used to estimate total state economic losses	**indirect and total economic losses for industry sectors affected** - total impacts are sum of direct and indirect output losses; multipliers used to derive total impacts for output, employment, earnings, value added
		Impact # 1 - Direct Economic Output Losses		**Impact # 2 -Indirect Economic Losses**	
air freight suspensions for affected US air cargo exports	**national**	**US shippers suspend production/sales**: industry output reduced for duration of suspension; US shippers based on FAF data	**reduced national output, employment, earnings and value added for industry sectors affected -** output of affected industries derived from BEA or other national data sources	**direct output losses expanded for multiplier effects -** output multipliers from RIMS or IMPLAN used to estimate total national economic losses	**indirect and total economic losses for industry sectors affected** - total impacts are sum of direct and indirect output losses; multipliers used to derive total impacts for output, employment, earnings, value added
		Impact # 1 - Direct Shipper Cost Impacts - Air cargo shipments reinstated from other supplier countries or regions		**Impact # 2 - Inventory Cost Increases**	
major resourcing of US air freight imports from other countries	**national**	**increased US shipper costs** - transport cost for US shipments; US shippers based on FAF data	**direct national transportation cost increases** - apply modal cost factors to change in ton miles and hours, to US TM/TH increase - apply ton to truck conversion factors as needed	**inventory cost increases** - cost of increased time in transporting freight to market and/or holding freight in inventory	**time value of freight** - calculated as change in regional ton hours x cost of capital per hour for private sector

Table 5-1F. Air cargo disruptions — long term impacts.

Supply Chain Response	Geographic Scope	Economic Impact	Economic Metric	Economic Impact	Economic Metric
		Long Term Impact # 1 - Moderate to Major Reductions in Economic Output, Employment, Earnings, GDP		**Long Term Impact # 2 - Major Impacts on Shippers from Sustained Shipment Disruptions, Inventory Depleted and Supply Chain Permanently Reorganized**	
air freight suspensions for affected US air cargo movements	**national**	**direct loss in industry output and sales -** industry output from BEA or other data	**total reduction in economic output, employment and earnings**: output multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added	**multiple long term responses** - 1) Shipper firms relocate out of US or 2) Shipper firms remain, permanently shifting supply chain to next nearest port	**lost economic output, employment, wage earnings, GDP**: In case of: 1) relocation: firm output permanently lost to US and total national economic activity falls; or 2) next best port permanently adopted: national industry output falls due to higher transportation and inventory costs
		Long Term Impact # 1 - Moderate to Major Reductions in Economic Output, Employment, Earnings, GDP		**Long Term Impact # 2 - Major Impacts on Shippers from Sustained Shipment Disruptions, Inventory Depleted and Supply Chain Permanently Reorganized**	
air freight suspensions for affected US air cargo exports	**national**	**direct loss in industry output and sales -** industry output from BEA or other data	**total reduction in economic output, employment and earnings**: output multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added	**multiple long term responses**- 1) Shipper firms relocate out of US or 2) Shipper firms remain, permanently shifting supply chain to next nearest port	**lost economic output, employment, wage earnings, GDP**: In case of: 1) relocation: firm output permanently lost to US and total national economic activity falls; or 2) next best port permanently adopted: national industry output falls due to higher transportation and inventory costs
		Long Term Impact # 1 - Small to Moderate Reductions in Economic Output, Employment, Earnings, GDP:			
major resourcing of US air freight imports from other countries	**national**	**persistent transport and inventory cost increases reduce business productivity and output** - shippers affected reduce output as a function of increased production costs	**total reduction in economic output, employment and earnings**: output elasticities applied to shipper cost increases, by industry; IMPLAN or other multipliers used to estimate total direct, indirect and induced economic losses for earnings, employment, output and value added		

5.2 Key Parameters

5.2.1 Type of Disruption

Although many types of freight transport/supply chain disruptions can occur and vary in details, the high-level methodology has combined these into three broad types that capture most of the possible incidents and also would be analyzed similarly. These are as follows:

- Major land freight transport link disruption (highway/bridge, Class I railroad, short-line railroad, inland waterway, pipeline, land-based international border crossing)—a partial or complete disruption to a major land freight transport link. Examples include the Minneapolis bridge collapse and the Baltimore rail tunnel fire.
- Major ocean/air cargo port disruption—major service disruptions to an ocean port or airport, or major disruption of direct intermodal connection(s) to the port. An example of this is the closure of the Ports of Los Angeles/Long Beach (LA/LB) due to labor disputes.
- Regional air cargo disruption—major disruption to air/air cargo operations over large areas or regions. Examples include the shutdown of European airspace as a result of the volcanic eruptions in Iceland.

These three disruption types correspond to the major row categories in Table 5-1.

Not included in Table 5-1 are large-scale national or regional disasters that cripple industrial output and normal social functioning for a significant period of time. In this case, major supply chain impacts can occur "at the source" of production. Impacts of this type can, and have, been shown to have very profound global economic impacts due to supply chain effects (other economic effects can also arise, such as disruptions to financial markets; reduced national income, consumption, and trade; loss of life; and other humanitarian needs). Prime examples include the March 2011 earthquake and tsunami in Japan and major flooding in Thailand in the fall of 2011. In cases such as these, key production sectors around the world can be significantly impacted. In the case of the Thai floods, computer manufacturers and assemblers around the world were rapidly affected. Thailand is a major global manufacturer of external computer disk drives; the disruptions to this component industry were quickly felt around the world. One estimate is that prices for these components were bid up by about 10 percent as a result of the disruption and resulting parts shortages (*New York Times,* Nov. 6, "Thailand Flooding Cripples Hard Drive Suppliers").

5.2.2 Supply Chain Response

As noted earlier, supply chains can be modified or will modify themselves in response to disruptions to the transportation system based on many factors, and the nature of the responses can be complex. Responses can also vary over time, so that for the shortest duration disruption, it is possible that a response of any kind is neither practical nor needed. Rather, shippers and carriers can simply wait out the disruption—shippers and producers, for example, can draw down inventories until the disruption is fixed and goods begin moving again across normal supply chain channels.

For the high-level methodology, a simplified typology of responses is developed. As highlighted in Table 5-1, these include

- Shifting freight transport to the next shortest/least-cost routing or facility—for example, if a major truck route is closed, trucks can detour to another route; if a port is shut down, import and export cargoes can be shifted to a reasonably nearby (next least cost or next lowest transport time) port, provided costs are not prohibitive and capacity is available. Port options are more complex—some import containers, for example, may be headed for interior U.S. land destinations, and other ports can pick up the slack. An example of this is when the Ports of Seattle and Tacoma served as an alternative port for some containers during the Port of LA/LB shutdown. However, in other cases, such as the transport of in-region cargo, no other port can be used because distances from the alternative port to the destination can become too great for cost-effective shipping.

- Freight may, in some cases, be shifted to other modes—for example, rail shipments can be transported by truck, although this becomes less economical as the line-haul distance increases.
- Goods may stop moving for the duration of the disruption—where no reasonable alternative routings or facilities are available, goods may simply not move, or in the case of disruptions to port intermodal linkages, may languish in port or near port storage and warehouse facilities.
- Supply chain responses can be different in the case of major regional or international port or air cargo hub disruptions—here it is possible that the disruption is of such scale and geographic scope that firms may have to quickly change their regional sourcing of goods—something seen quickly, for example, after the 2011 Japanese earthquake and tsunamis. In this case, until supply chains are able to adjust by resourcing major products or inputs, severe global shortages may occur. Industrial output may be suspended or, alternatively, prices for disrupted products may increase substantially.

A mix of responses is not only possible, but likely, depending on the mix of cargo types and their origins and destinations. For this reason, it is difficult to treat "freight" through a point as a homogenous flow; rather, some differentiation of freight flows by commodity and origin-destination is highly desirable from a methodological standpoint, assuming the data are available.

5.2.3 Impact Geography

Economic impacts can vary significantly when viewed from different geographic/jurisdictional perspectives. For example, freight that originates or terminates outside of a given region (i.e., that is not shipped by producers within the region, but simply moves through) may be of little economic consequence to regional or local authorities or planners. At the same time, where a port that employs thousands of people in a region is shut, a long disruption can significantly affect the regional economy, both due to impacts on regional shippers, as well from lost port employee wages, business losses to port suppliers, and to the port itself in terms of lost cargo handling fees and tariffs. On the other hand, where freight shifts fairly seamlessly from a given route or facility to a reasonable alternative path, the impacts from a national perspective can be negligible.

The high-level methodology considers economic impacts from the local/regional, state, and national perspectives.

5.2.4 Short-Term vs. Long-Term Timeframe

Many, even the most apparently serious disruptions, will be of relatively short duration. For example, as described in its respective case study, Baltimore's Howard Street Tunnel rail fire caused rail cargo disruptions/diversions of only several days (although street-level disruptions to local traffic, utilities, and commercial business activity lasted considerably longer). However, a highway bridge collapse can take months or even years to remedy. Supply chain responses can be very different over time—in the very short run, goods can simply be held back as inventory is drawn down. A less favorable short-run case is where goods cannot flow, and manufacturing or other economic production may cease for a time. Over time, new routings or modal shifts can be established and built into supply chains as a more normal practice. Higher transport and possibly inventory costs can be borne by shippers for a time, as these shifts can effect a "bandage" over the disruption. For long persisting disruptions, however, firms and shippers may be forced to completely overhaul their supply chain networks, as the persisting increases in transport and inventory costs mount. In this case, some firms may seek to change their sourcing of inputs, rely on alternative warehousing locations, or, in the worst case, might consider relocating all or some operations.

5.2.5 Economic Impact Type

A simplified typology of economic impacts, including both impacts and metrics, is detailed under Columns 4 and 5 in Table 5-1. Although specific impacts can vary in some details depending on the type of disruption, the geographic perspective, and the timeframe, the high-level methodology groups impact the following categories:

1. **Direct transportation (shipper) cost increases**—These are the direct cost increases of moving freight across an alternative path, through another intermodal or port facility, or via another mode. Direct transport cost differentials can be derived, assuming some information about the origins, destinations, modes, and location of next-best alternative. Costs can be estimated as a function of changes in freight ton hours, miles, or both.
2. **Inventory cost increases for commodities delayed**—For commodities that have a high value and/or are time sensitive, the costs of slower transit times can be real. Freight economics identifies several reasons for these costs, including the costs of extra storage and delays in getting time-sensitive goods to market. Typically, such costs are measured against the market value of freight as a function of the delay, measured in freight ton-hours. Inventory costs can be estimated by multiplying the additional dollar value of freight delayed by the duration of the delay and by the opportunity cost of capital (discount rate or prevailing private-sector interest rates) prorated for the period of disruption.
3. **Reduced economic output as goods cannot get to market**—Industry output in an area will fall when freight disruptions compel freight users (shippers) to suspend production or when retail goods cannot be brought to stores for final sale. These effects may sometimes be referred to as general equilibrium impacts, although true impacts of this type would consider supply, demand, productivity, output, and price adjustments over time. Over a period of time, a region may see significant reductions in economic output and associated employment and earnings. A shutdown in production or significant cut back in sales will have a direct impact on those sectors affected. As output (supply) falls, there can also be price effects—prices can rise—but the output reductions would have to be large enough to have significant macroeconomic effects nationally or regionally. Price effects are not considered in the high-level methodology.
4. **Reduced economic output due to persistent, higher supply chain costs**—Significant increases in transportation and inventory costs, when sustained for long periods of time, can result in reductions in producer firms' economic output. Resources effectively become less efficient as they cost more, and reductions in those resources can be expected to lead to fewer inputs and less output. In the short to middle run, other things cannot be "substituted" for transportation (e.g., more inventories) so the increases in costs reduce the overall output of shipper firms. These impacts will be smaller than when firms must altogether shut down or greatly reduce production due to a complete break in their supply chain.
5. **Multiplier effects**—Whenever economic output in a region falls, either because of temporary or longer term production cut backs, or because of a contraction of output due to higher producer costs (due to higher transport and inventory costs), that reduction will carry over to other firms, which sell to the directly affected business, or due to reductions in household earnings, which affect consumption across many other economic sectors. These "multiplier" effects (indirect and induced impacts in the nomenclature of I-O analysis) are typically used in economic impact assessment.

Multipliers are derived from several possible sources, but all are based on an I-O model of the regional, state, or national economies. Reduced economic output on the part of producers, as well as reduced final sales for retailers and wholesalers, are represented in I-O modeling as reductions in final demand.

6. **Total employment, earnings, and gross domestic product (GDP) impacts**—Reductions in final demand can be further used to estimate reductions in employment, wage earnings, and value added. Value added represents final sales for all producers in an area minus the costs of intermediate goods purchases used in production. The sum of value added by all sectors in an area is one way to measure gross product, the best measure of economic activity in an area. By summing changes in value added, changes in gross regional, state, or national product can be derived.

   Existing economic impact models such as the PRISM and TREDIS models are both effective in estimating these impacts. For example, PRISM utilizes the output of freight demand models to estimate changes in freight costs due to changes in the freight network (including possible reroutings), assigns these costs to industries, and utilizes researched elasticity assumptions to "translate" freight transport cost changes into industry output, employment, earnings, and value added effects, both for the industries directly affected and for other economic sectors. This is done utilizing IMPLAN-derived economic multipliers.
7. **Port, airport, and other intermodal facility impacts**—The high-level methodology includes regional and state economic impacts unique to ports and airports. These facilities, and perhaps major intermodal rail facilities, are regional economic engines in their own right. When a major port such as LA/LB is closed for a length of time, direct economic losses can accrue to a region as workers may (depending on actual labor practices) be furloughed and as port supplier firms lose business sales. In addition, these impacts have an effect on household earnings, which in turn, generates its own set of induced multiplier effects.

   Existing economic impact models such as the MARAD Port Economic Impact Kit are available to estimate such impacts.

5.3 Key Data Inputs and Major Assumptions

To implement the high-level methodology, data must be obtained—or assumed—that capture the types of commodities being slowed or halted by the disruption, their approximate origins and destinations, and modes of transport. These must then be related to the industry structure of an area, so commodity flows can reasonably be associated with the regional, state, or national industries that are shipping the commodities and that are therefore impacted by disruptions.

Gathering this information can be a daunting task and, clearly, for the methodology to work, it will almost always be true that some simplifying assumptions will be required. At a minimum, simple data sets readily accessible will be required. Data or assumptions required will include the following:

- Commodity flows affected—Requires information about commodity origins and destinations, types of commodities, value or value class, and transport mode. FAF3 data may be sufficient in most cases when applying the high-level methodology (but **see discussion with respect to Table 5-2**).
- Shipper industries affected—As noted, commodities must ultimately be related to the economy of an area, because the economic impacts relate to the industry structure. Conversion tables, which relate commodities to industries, can be developed for this purpose. I-O make-use tables can also be used, since these relate commodity sales to industries purchasing.
- Commodity value—Time value of freight (inventory value) is a function of commodity value and can differ significantly for different commodities. As an alternative to a detailed commodity/

Table 5-2. Summary of potential freight flows data sources, by model-relevant key characteristics (Step 2).

Network Flows Data Sources	Source of information	Available by mode?	Trip distance information	Available by commodity NAICS?	Link specific flows	Forecast data available?	Behavioral sensitive to network changes
Truck traffic counts by highway segment and possibly seaport	MPO or state DOT supplied	Truck only	Usually no	No	Yes	Usually no	Yes
Customized link node Travel Demand Model	Usually MPO or state DOT where statewide TDM model available	Usually some truck data for highway network	Yes	Usually no	Yes, for truck	Yes	Yes
Freight Analysis Framework (FAF)	From FHWA	Yes	Yes	Yes	Yes for truck	Yes	No
TranSearch	Purchased from private vendor	Yes	Yes	Yes	No	Yes	No
Commodity Flow Survey Data	From BTS/Census	Yes	Yes	Yes	No	No	No

value analysis, it may be sufficient to break freight into rough time value classes—high, low and medium time sensitivity. For example, bulk commodities moving by barge are of very low unit value and are not typically time sensitive; by contrast, perishable food or high-value-added electronics (e.g., parts made to assemble an iPhone) would be rated high in time value.

- Alternative transport paths—Without an elaborate freight transport model, assignment of disrupted freight to alternative paths can usually be made based on knowledge of the surrounding transport system and other factors. Educated guesses are a reasonable option in this case, including potential for mode shift. Mode shift potential (e.g., shift from rail to truck) can be informed by knowledge of origins and destinations of the cargo and the distance of transport.

There are many commodity flow data options, including freight flows data, transport cost data, and other requirements. Table 5-2 summarizes data options that might be typically available for freight flows in a particular application of the high-level methodology. In addition to the above, ocean port cargo data can usually be obtained directly from the port, the U.S. Army Corps of Engineers, or other maritime data sources.

In addition to its 123 (in 2007) region-to-regional national commodity flows by mode matrix, the public domain FAF database also supplies a set of route-specific highway (truck) volumes for the nation's interstates and other major intercity truck routes that can be useful to corridor-level analysis. Where rail or inland waterway routes are involved, STB's railcar waybill data and the U.S. Army Corps of Engineers' Waterborne Commerce data sets (cf Section 2.3.1) can be used to develop route-specific flows. Where a more detailed connection between O-D and commodity-specific flows and modal-corridor-specific flows are needed, further disaggregation of FAF inter-regional O-D flows may be required. While more detailed spatial and sectoral associations between industrial activity are more appropriate to the in-depth level of analysis and require additional resources, IHS Global Insight's inter-county commodity flows matrix, known as its Transearch database, offers readily obtained, if proprietary, data sources (http://www.ihs.com/products/global-insight/industry-analysis/commerce-transport/database.aspx). The IMPLAN Website also lists a recently developed doubly constrained gravity-model-based inter-county trade flows matrix. Such proprietary options trade off development effort and time against availability, transparency, and some flexibility in adaptation of county-level trade-cum-freight flow data. A third option is for a state DOT to generate its own O-D matrices using Census and other non-proprietary data sources. At the time of writing, NCFRP Project 20, "Guidebook for Developing Sub-National Commodity Flow Data," is underway, looking at methods for combining FAF version3 region-to-region flows with other generally available data sources in order to produce more detailed corridor-level freight flows (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2663).

5.4 Economic Impact Rules of Thumb

Once a reasonable set of assumptions has been made about the likely supply chain outcomes and responses (e.g., freight diverted to another route or mode, freight does not move and shippers reduce output or suspend production, producers re-source inputs from other locations or move their production to other locations, etc.), the economic impact of those outcomes can be estimated.

Figure 5-1 shows the basic concept that underlies the rules-of-thumb approach to estimating economic impact from disruptions. The economic impact of any particular disruption would depend primarily on the commodity characteristics, the characteristics of the disruption, and the costs associated with different elements of the cost structure (e.g., transport/logistics costs, inventory costs, productivity, and output losses).

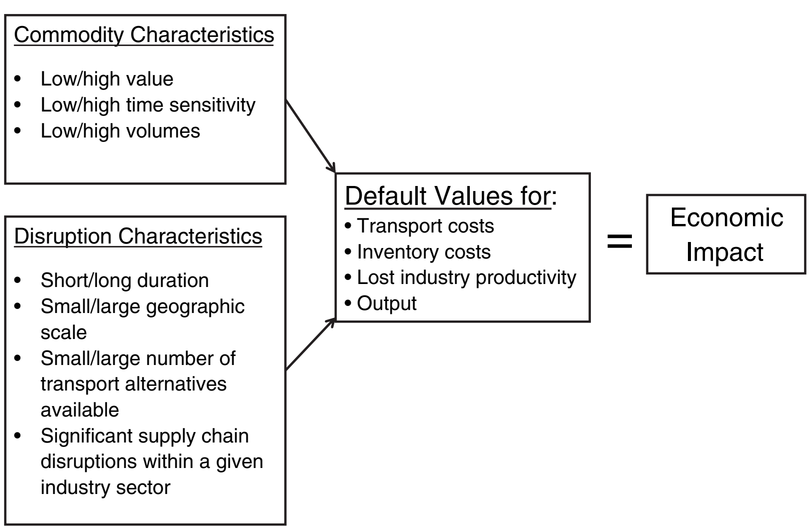


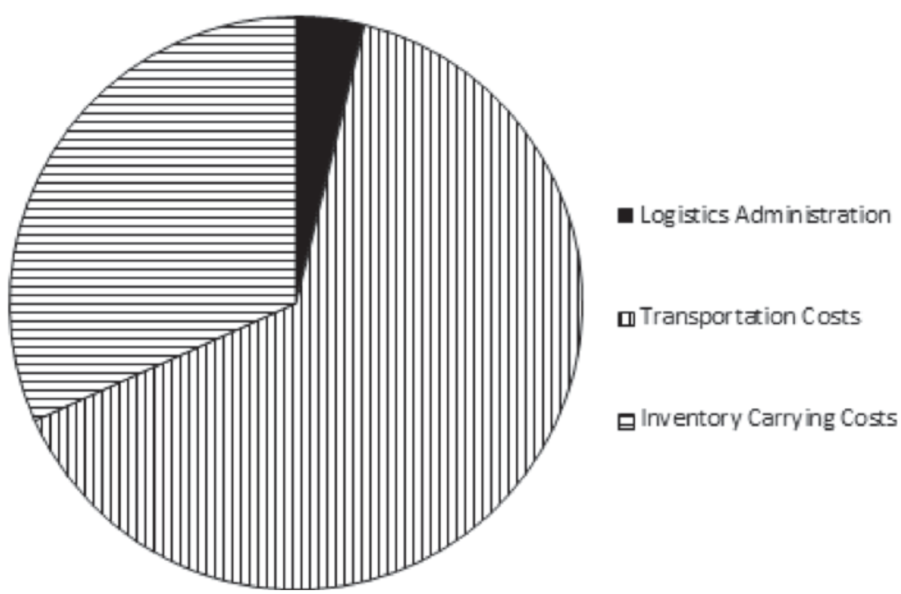
Figure 5-1. Basic concept for "rules of thumb" analysis.

The basic economic impacts estimated in the high-level methodology are as follows:

- Transport/logistics costs—These are primarily cost increases incident to shippers/beneficial cargo owners (BCOs), or transportation providers. They primarily include direct freight transport costs and inventory costs and are typically a short- to middle-term impact. Figure 5-2 represents a current estimate of the shares of total logistics costs attributable to direct transportation and inventory.
- Regional economic impacts—These comprise wider economic impacts reflecting losses in regional output, sales, employment, wages, and GDP. They comprise any or all of the following impacts:
  - Lost economic output, employment, earnings, and GDP resulting from suspension of production or final sales due to breaks in freight shipping such as could occur when a major ocean port is shut down, the freight rail network is cut at some location, or a major shipping oil pipeline is cut (short run).
  - Reduced economic activity (output, employment, earnings, and GDP) from persistently higher transport costs (mid to long run).
  - Impacts on specific facilities such as sea ports or air cargo ports and multiplier effects within the region.

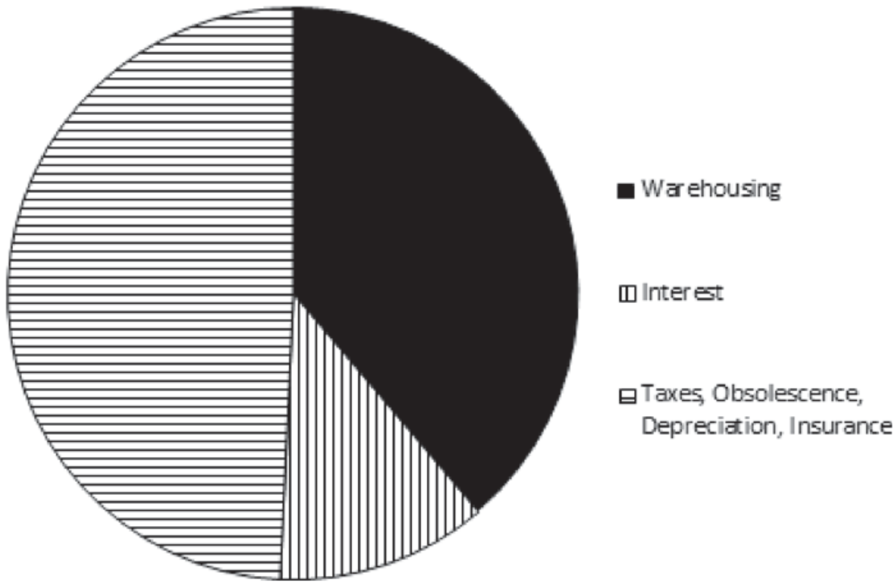
Default rule-of-thumb values for estimating impacts are provided below and may be considered as reasonable approximations for immediate estimates of potential economic impacts of disruptions, where results are needed quickly or the time and costs of collecting detailed data or performing economic modeling are unavailable. The rules of thumb cover the following areas:

- Logistics costs
  - Direct unit transport cost values, by mode (e.g., transport cost per ton-mile and per vehicle-mile by truck)—Unit default costs for the rules of thumb are derived from a range of sources including those from ATRI, Association of American Railroads (AAR), FHWA, Vachal et al. (2005), the Arkansas River Historical Society (inland barges), and Bitzan et al. (2002) (on short line-railroads).
  - Unit inventory value of commodities, by commodity and value type (e.g., inventory cost per ton-hour of high-value manufactured products moved by truck)—Inventory costs can



Source: http://ops.fhwa.dot.gov/freight/freight_analysis/econ_methods/lcdp_rep/index.htm#Toc112735358

Figure 5-2. Logistics costs components.



Source: http://ops.fhwa.dot.gov/freight/freight_analysis/econ_methods/lcdp_rep/index.htm#Toc112735358

Figure 5-3. Components of inventory-carrying costs.

be viewed as composed of a number of cost elements. As shown in Figure 5-3, inventory costs include direct costs of warehousing (which, in turn, includes items such as real estate carrying costs, maintenance of warehouse structures, etc.); interest on the value of goods delayed in getting to market; and depreciation, taxes, insurance, pilferage, and loss, etc. Inventory costs are estimated based on the estimates reported by Macrosys (2005) and FHWA (2006).

- Regional economic impacts
  - Direct output losses from disrupted production or sales—Total impacts in the high-level methodology are estimated per $1 million in **direct** output loss. Where specific industry output for disrupted industries in a region can be identified, the total economic losses in output, employment, wage earnings, and GDP can be estimated. Basic economic statistics such as U.S. Bureau of Economic Analysis regional and state GDP by industry data and U.S. Bureau of Labor Statistics (BLS) industry output data can be used to estimate **direct** output losses by industry in a given region or state on an annual basis. For given regions and areas, output by detailed NAICS industry class can be estimated based on national output to employment ratios, multiplied by the area's employment in that industry. Employment data by NAICS are readily available for states, regions, and metropolitan areas through BLS or state economic data bases. Default impact multipliers would be applied to estimated output losses.
  - Indirect output losses from sustained increases in transportation cost and time—Total regional impacts on employment, output, earnings, GDP, and by industry class resulting from long-term increases in transport and inventory costs. Impacts are estimated in the high-level methodology as a function of logistics cost increases for a given commodity/industry group. The rate at which increased transport and inventory costs result in changes (reductions) in the output of those industries is based on transportation "elasticity factors" that relate industry output (final demand) to logistics costs. Models such as Parsons Brinckerhoff's PRISM Model can be used to estimate the full economic impacts of short-term industry transport and logistics cost increases on commodities and industries within a region. PRISM utilizes IMPLAN I-O data for this purpose.
  - Total regional impacts on employment, output, earnings, and GDP from reduced or disrupted port throughput and revenues—Typically, short-term economic losses when large maritime

ports (or other large intermodal facilities such as major intermodal rail hubs or interior ports) slow or become inactive, cargo is not handled, and port revenues cease to be earned. Port economic multiplier (or spinoff) impacts are also lost. Direct port impacts, including reduced container or other cargo throughput volumes can be estimated utilizing basic throughput data from the port itself, from Waterborne Commerce data, or from American Association of Ports data.

Table 5-3 shows the impact multipliers that constitute the rules of thumb as derived from this research. The principal sources of the parameter values used are noted below this table. In applying these rules of thumb and parameter values, certain guidelines and limitations apply as follows:

- Direct transportation costs—Average unit transport costs for modes must be treated as very approximate. Unit costs vary significantly within the modes by type of service, distance, speeds, equipment types, cargo type, geographic location, and multiple other factors. For example, truck costs will be higher in the New York metropolitan area than for the nation as a whole, since wage and fuel costs and taxes are higher there. Costs in metropolitan areas will also be higher than national averages, since congestion will affect driving times, rates of fuel consumption, etc. NCFRP Project 26, currently underway, is expected to provide detailed costing information and, when completed, can be used as a reference for analysts seeking to apply the high-level methodology.
- Inventory costs—Costs can vary significantly for specific commodities, and grouping commodities into rough value classes, as in Table 5-3, should be considered very general approximations. Variations in inventory costs by mode may be considered preliminary in nature here and arise because of the simplified methodology used for deriving default values, which are based on a percentage of direct transport costs. Variations in inventory costs per **ton hour** of delay in freight transport will be due primarily to cargo value, rather than mode.
- Regional economic impacts—Judgment must be applied to the question of whether disruptions will result in a stoppage of production (or sales for retailers), inventory draw down, changes in sourcing of inputs, or other market- and production-sector responses. These judgments should be based on the following considerations:
  - Timing—impacts are likely to be significant only if disruptions extend beyond several weeks, which would represent the period of inventory turnover for an average producer, retailer, or wholesaler (see below).
  - Severity and geographic scope of the disruption: widespread disruptions covering a large area and many industries and shippers and affecting numerous links along the supply chain will generate the most significant general equilibrium impacts.
  - Rate of inventory turnover (for assessing the likelihood of existing inventory draw down)—as noted, inventory turnover will typically be several weeks to a month, but different industries will have different inventory draw-down rates.
  - Other factors specific to the circumstance.
- Direct facility impacts—Direct facility impacts relate to potential losses in regional economic activity resulting from a “stand down” of the facility itself. When a major port such as Los Angeles/Long Beach is closed, regional economic activity will be affected to the extent that port workers are laid off or furloughed, and as support businesses outside the port itself (e.g., drayage services, ship maintenance, bunkering services) lose sales. Port revenues will also be directly affected, although those losses would be partially offset by reduced marginal expenditures by the port itself. To illustrate, if a port handling 1,000 TEU per day (a mid- to big-size container terminal) is shut down for 10 days, then there would be 6,700 person days of lost employment, $1.07M in associated lost wage earnings, and state/regional GDP would fall by $1.60M.

Table 5-3. Economic impact rules of thumb—default values.

Direct Transport Costs (per mile, hour)	Truck	Class I RR	Short Line RR	Inland Waterway/Barge
Per ton-mile	$0.07	$0.03	$0.04	$0.01
Per ton-hour	$2.63	$0.52	$1.07	$0.06
Per vehicle-mile	$1.39	$1.90	$4.07	$14.55
Per vehicle-hour	$59.03	$39.56	$101.70	$87.30
Inventory Costs (per ton-hour)	**Truck**	**Class I RR**	**Short Line RR**	**Inland Waterway/Barge**
High-value manufacturing	$1.05	$0.22	$0.45	n.a.
Low- to moderate-value manufacturing	$0.92	$0.19	$0.38	n.a.
Low-value bulk commodities	$0.74	$0.14	$0.29	$0.02
Perishable agricultural	$1.19	$0.23	$0.47	n.a.
Regional Economic Impacts	**Total Output (millions)**	**Total Employment (job years, 000s)**	**Total Wage Earnings (millions)**	**Total GDP (millions)**
Direct Output Reductions (per $ million direct output loss, 2009$)				
Manufacturing	$1.89	9.1	$0.42	$0.75
Services	$1.59	12.6	$0.51	$0.92
Retail and wholesale	$1.47	13.1	$0.49	$0.92
Agricultural, natural resources	$1.69	9.8	$0.41	$0.86
Higher Freight Transport and Inventory Costs (per $ million transport cost increase, 2009$)				
Manufacturing	$1.27	4.3	40.33	$0.50
Services	$1.24	10.5	$0.58	$0.71
Retail and wholesale	$1.14	8.7	$0.50	$0.77
Agricultural, natural resources	$1.19	8.2	$0.48	$0.60
Direct Facility Impacts (per 1,000 TEU per day of impact	**Total Output (millions)**	**Total Employment (job years, 000s)**	**Total Wage Earnings (millions)**	**Total GDP (millions)**
Ocean port	$412,600	$670	$107,200	$162,400

Sources: **Direct Transport Costs**. For truck costs. ATRI, 2010, for Class 1 railroads AAR (2011), for short line railroads Bizman et al, 2002, for inland waterways the Arkansas River Historical Society, 2010 and Vachal et al., 2005.

- **Inventory Costs**. Macrosys (2005), FHWA (2006)
- **Regional Economic Impacts**
  - **Direct Output Reductions**. IMPLAN; US Bureau of Economic Analysis, RIMS II National Type I Direct Multipliers, 2008 updated to 2009 dollars
  - **Higher Freight Transport and Inventory Cost impacts.** Parsons Brinckerhoff PRISM model; IMPLAN
- **Direct Port Facility Impacts**. Parsons Brinckerhoff port impact analyses (various); Le-Griffin, Hahn-Le and Melissa Murphy, "Container Terminal Productivity. Experiences at the Port of Los Angeles and Long Beach, Feb. 2006, University of Southern California, Dept. of Civil Engineering; ILA annual average earnings estimates http://www.ehow.com/info 8592745 longshoreman-salary.html

To estimate impacts in greater detail and to refine the "default" values presented above, various sources can be consulted. These include the following:

1. Freight transportation cost models—For the purposes of estimating transportation cost impacts, a consistent treatment of transportation costs is required. This means that the costs computed for each mode and each source-market pair should include the same generically defined set of cost elements. For the most part, freight costs are obtained from three sources (as freight rates based on averaging over a large number of individual shipping contracts, from statistically based freight costing or freight rate models, and from component-by-component constructed engineering cost models). Costs are usually derived on a commodity- and mode-specific basis.
   - Statistical cost models: These costs are usually based on regression modeling, using either cross-sectional or time-series data for model calibration purposes, and typically include travel distance or distance-based average operating cost, travel time, and one or more measures of service quality (notably, measures of service reliability such as on-time arrival percentage or standard deviation of delivery times). There are many examples of regression-based freight rate models. Commercially available products include Global Insight's COSTLINE© family of rail and barge costing models (http://www.ihsglobalinsight.com/gcpath/Costline.pdf), and Commonwealth Logistics Rail Costing System© (http://commonwealthlogistics.com/). Benson et al. (1999) used historical data to estimate container rates for agricultural commodity cargos. Rate calculators based on this work can be found on the IODA's Ocean Rate Bulletin Website. (http://www.ams.IOda.gov/tmd/Ocean/calculatIons.htm).
   - Engineering cost models: These models now often take the form of a detailed spreadsheet model summing costs over a mode's principal cost components and producing a total dollar valued cost per ton or per ton-mile. Examples include ITIC-IM, the U.S.DOT's Intermodal Transportation and Inventory Cost Model Cost Model (FRA 2005), ORNIM, the U.S. Army Corps of Engineers Ohio River Navigation Investment Model (ORNL 2001), the Surface Transportation Board's Uniform Railroad Costing System (URCS) software, and the Truck Load Analysis Model developed by Berwick and Faroog (2003). There are also rate-based commercially available software packages such as U.S. Rail Desktop that, through sampled rate data, provides carrier costs and margins and benchmark rail rates for carload, trainload, and intermodal shippers (http://www.IOraildesktop.com/). Each of these models includes a wide range of logistics as well as pure "transportation" costs, and each offers a means of reconciling fixed and variable costs for economic analysis purposes. NCFRP Project 26, is looking in depth into this freight cost modeling literature.
2. Economic impact models—These models relate direct reductions in industry output to overall regional or state economic activity and are derived from input/output modeling sources, such as IMPLAN. More advanced models, which relate increased transportation costs to economic behavior and output of firms, would include models such as PRISM and TREDIS. The MARAD Port Economic Impact Kit is a useful and available tool for estimating overall economic impacts of port closures or disruptions, and that model can likely be extended to airports as well. Other airport economic impact modeling tools are described in research monographs such as *ACRP Synthesis 7: Airport Economic Impact Methods and Models* (http://onlinepubs.trb.org/onlinepubs/acrp/acrp_syn_007.pdf).

Additional rules of thumb were inferred from the case studies. The case studies identified three initial considerations in framing the short- and longer term impacts associated with supply chain disruptions. All three of the following factor into the economic impact assessment:

- Geographic scale of the disruption—The larger the geographic area affected by the disruption, the greater the impact on the supply chain. This includes the ability of other supply chain modes and routes to provide alternative capacity. For example, 9/11 temporarily shut all airports, seaports, and U.S. borders. This caused disruptions to those industries that kept minimal inventory on-hand and relied on international movements (e.g., automotive assembly lines). Hurricane Katrina involved substantial damage to miles of railroad infrastructure, which had to be rebuilt. In contrast, the Howard Street Tunnel fire affected the major north-south route of a Class I railroad, but was limited in geographic scope. Accordingly, time-sensitive rail moves could be shifted to alternate routes.

- Length of time required for infrastructure repair/reopening facilities—The longer the time required to repair the infrastructure, the greater the level of supply chain disruption and related economic impacts. In the case of the Howard Street Tunnel fire, the route was reopened within days, minimizing the short-term disruption on rail movements. Similarly, the Port of New York and New Jersey was reopened quickly after 9/11, minimizing the impact on vessel operations.
- Forced re-thinking of supply chain practices—In addition to the above, disruptions or additional costs to the supply chain can result in a re-thinking of practice, which in turn can have economic impacts. For example, the 9/11 closure of JFK International Airport (JFK) forced air cargo customers to try alternate airports. Some of these customers found the alternate airports less expensive or better than the "status quo" use of JFK. As a result, JFK's air cargo customer base eroded. Similarly, the 2002 West Coast port strike resulted in major retail customers adopting a port diversification strategy, meaning companies switched to using multiple ports along several U.S. coasts for the receipt of cargo rather than relying largely on one port. The port diversification strategy resulted in increased traffic and economic value for some ports.

5.5 Illustrated Application of Methodology to Representative Case Study—Northridge Earthquake

A case study narrative of the Northridge earthquake was presented in Section 4.4. In this section, the high-level methodology is applied in simplified form to illustrate its application, the types of assumptions required, and the outputs estimated. There is adequate information in the case study to apply the methodology in a credible manner, supplemented by information from other sources. Importantly, the case study includes estimates of economic impacts generated by other, more detailed studies of the earthquake's economic effects. This provides information against which the high-level methodology can be evaluated.

A more comprehensive analysis of the traffic and supply chain effects of the Northridge earthquake can be found at http://ntl.bts.gov/lib/jpodocs/repts_te/13775.html#_Toc25646695.

Input Assumptions

Average Annual Daily Truck Traffic (AADTT) = approximately 20,000 trucks (http://www.goldenstategateway.org/IOer_content/Interchange_Spring_2011_WEB.pdf).

- Duration of disruption = 4–6 months.
- Truck (and other I-5) traffic detoured to longer and lower speed routes:
  - Caltrans and other surveys indicated major drops in traffic on I-5 leading to the affected sections.
  - Rerouted traffic traveled significant additional distances to use alternative regional highway corridors such as I-15 and I-110.
  - SR 14 bypass lanes (the primary detour route) accepted 75 percent to 80 percent of pre-quake I-5 trips.
  - Parallel routes all operated under congested conditions for the 4–6 month duration of the disruption.

  - By the fourth month, most major shippers using I-5 (96 percent) had returned to pre-disruption supply chain and routing practices.
  - Surveys indicated that 81 percent of trucks were rerouted and 69 percent were rescheduled, and driver overtime increased 55 percent. Other strategies included consolidated loads (29 percent) and reduced pick-up and delivery frequencies (38 percent).
- Average trucking detour distance assumed to be 25 miles.
- Average increase in truck delivery time of .75 hours.
- Post-event surveys indicated business disruptions, with about 5 percent surveyed indicating significant interrupted supplies. Of that, assume 1 percent output loss.
- Average truck freight assumed to be of moderate to high value.
- Average truck payload = 10 tons.
- In the absence of detailed truck commodity and industry data, industry sectors are assumed to be a mix (an average) across manufacturing, services, retail and wholesale, and agriculture and natural resources.
- Because I-5 was restored in stages extending over 4 to 6 months at various locations, the average truck impact is assumed to be 5 months.

Simplified Calculations

Based on the above, the following simplified calculations of economic loss are made based on the high-level methodology. Losses are expressed in 2009 dollars.

- Direct transport cost increases
  - 20,000 truck trips × $1.39/truck mile × 25 mile detour = @$700K per day for detour distance
  - 20,000 truck trips × $59.03/truck hour × .75 hours = @$900K per day for delay
  - Total for average of 5-month duration = $105M for distance + $135M for delay = @$240M
- Inventory cost increases
  - 20,000 truck trips × 10 tons × .75 hours/truck × $1.00 inventory cost/ton hour = $150K/day
  - Total for average of 5-month duration = @$22.5M
- Wider regional economic impacts—increased supply chain costs
  - Total direct supply chain (logistics cost) increase = $265M (from above)
  - Total lost output = $265M × 1.21 = $320M
  - Net regional economic loss (multiplier only) = @$55M
- Wider regional economic impacts – disrupted production/output/sales
  - 20,000 daily truck trips × 150 days × $8,000 (FHWA, Value per Ton of IO Freight Shipments by Mode, 2002) average truck payload value × 1 percent lost output/final sales = $240M
  - Total lost output = $240M × 1.66 = @$400M
- Summary impacts
  - Logistics cost increase = @$265M
  - Net regional economic impact
    - Due to supply chain cost increases = $55M
    - Due to disrupted production/output, sales = $400M

Total Logistics Cost Increases and Lost Regional Output = @$720M

The combined figures above, approximately $265M in direct logistics cost increases and another $455M in net lost regional economic output, compares favorably to estimates made by Gordon et al. (cited in the Northridge case study) of $769 million in output losses attributable to business logistics cost increases.

CHAPTER 6

Conclusions and Future Research

6.1 Conclusions

This project has examined the characteristics of disruptions to freight networks and developed two approaches to analyzing the associated economic impacts. The conclusions from this research relate to three important areas—characteristics of the disruptions and network responses themselves, modeling and analysis approaches, and the proposed methodologies for analyzing the economic impacts of disruptions.

6.1.1 Disruptions and Network Responses

In many of the cases studied for this project, the freight system responded quickly to the disruptions by either rerouting or using other means of delivering cargo. In such cases, the economic impacts to the carriers and customers were limited and regional. In a few rare cases, such as the port shutdown in Los Angeles/Long Beach, the economic losses were much greater. Several characteristics of the disruption and network response are important to consider.

- The spatial or geographic scale of disruption will likely have a direct bearing on the magnitude of the economic impact. For example, the closing of a major port or key links in a land transportation network could have negative impacts throughout the supply chain, assuming little redundancy in moving goods on alternate paths.
- Different types of disruption could have a range of direct and indirect economic impacts. For example, the removal of one critical link or mode in a network could create a bottleneck that might or might not have important consequences to goods flow. In the situation where a single mode is disrupted, shipments are likely to transfer to alternative modes. On the other hand, widespread network disruption (for example, due to floods and hurricanes) could have a multitude of overlapping and connected economic impacts.
- The characteristics of the freight being disrupted will also affect economic outcomes; disruptions of high-value, time-sensitive freight within a low-inventory, just-in-time supply chain will create larger economic impacts.
- The temporal nature of disruption will also have potentially important economic consequences. A short disruption, that is, one lasting a day or up to a week, might cause some temporary or short-term economic loss, but overall would have minimal economic impacts. However, one lasting a much longer time could have severe consequences depending on how industries and supply chains adjust.
- The economic impact of severe bottlenecks and disruptions could affect a wide range of supply chain participants, not just the ocean carriers, truckers, railroads, and shippers that are using the network to transport the goods. These participants include public agencies, local labor unions, local retailers, warehousing and distribution providers, and potentially a significant

number of consumers and economic organizations throughout the nation. The geographic incidence of impacts can shift over time as well.

- Network redundancy is a very important characteristic of economic impact. If, for example, goods flowing through a particular bottleneck can be rerouted without significant economic costs, the overall economic impact of a bottleneck could be minimal, ignoring for a moment the economic consequences to the local economy.
- The global goods movement supply chain is a multi-tiered system with various entities, stakeholders, networks, and modes involved that span a huge physical space and by their very nature are susceptible to natural and human-caused disruptions. International supply chains are also intricately interconnected.
- In case of a major event, such as a terrorist attack or an earthquake, standard risk mitigation measures, such as increasing safety stock, diversifying supply base, and building redundancy into logistical systems, may or may not afford much protection from damage.
- Disruption resistance (security) and tolerance (resilience or recovery) are both important measures in disruption management. These measures have to be balanced with concerns regarding productivity, while promising to provide sufficient benefits to justify costs.

6.1.2 Modeling and Analysis Approaches

A number of important issues for economic impact modeling were identified from this research, as follows:

- Various types of economic models can help estimate the potential for losses due to a disruption in the supply chain. These range from simple logical frameworks to complicated dynamic economic simulations. However, it is important to understand the underlying assumptions of these models, particularly with regard to resiliency of, and interdependencies among, businesses and infrastructures. The order of magnitude of loss estimation can be greatly affected by these assumptions.
- Cargo can shift to alternative modes when disruptions occur. The extent and nature of this shift will depend on many factors, such as whether the alternative mode serves the same geographic markets, the degree of redundancy and flexibility in the system, the economics of goods movement for different modes (e.g., low-value-added bulk goods moving by barge will not likely shift to truck, but rather to rail as the next best alternative), and the available capacity on alternative modes. Analysis methods must have the capability of estimating the level to which mode shift will occur.
- Whether goods can be shipped economically via other modes depends, in addition to the availability of service, on the value and nature of the cargo itself. High-value commodities or commodities that are otherwise time-sensitive, such as air cargo, may not economically be shifted to slower modes. This could have major negative effects on some parts of the country.
- The spatial level of the disruption can affect the degree of impact, as well as the types of models used in the assessment. The time dimension is especially important and merits some extra discussion. In the short run, impacts may be smaller under "normal" supply chain conditions, because there will be inventory to fall back upon. In the long run (i.e., for very long-term disruptions), the impacts may also be relatively small in an absolute sense, because both supply chains and industries may adjust. However, the spatial and distributional impacts may be significant to the extent that adjustments become permanent.

Assessing economic effects has to take into account the nature of the methodologies being used. For example, a disruption that shifts shipments from rail to truck may require that far more truck drivers be used. Some economic models would see this as a positive impact—more workers are being employed. However, from a user perspective, the system has become potentially less efficient and not enough drivers and/or highway capacity may exist to handle the increased shipments.

In other cases, the methodologies might rely on tools such as scientific surveys. Accordingly, the analysis of disruptions may require more of a "tool kit," rather than a "one-size-fits-all" model, organized within a consistent methodological framework. Certainly, data issues currently warrant such a tool kit approach. Obtaining data inputs for the high-level approach was not the easiest of tasks, given the wide range of responses and costs possible in any given situation. Local knowledge is invaluable here, although putting a specific numerical value on local insight remains a challenge that may require a search for local data in order to produce suitably accurate/acceptable input parameters.

6.1.3 Methodology for Assessing Economic Impacts of Freight Network Disruptions

The high-level methodology, based on the concept that the economic impact of any particular disruption would depend primarily on the commodity characteristics, the extent and nature of the disruption, and the costs associated with different elements of the cost structure (e.g., transport/logistics costs, inventory costs, productivity and output losses), is a useful sketch analysis tool. It can provide the user with an estimate of likely economic costs associated with any particular type of disruption.

The more detailed methodology depends on a much higher level of detail and more sophisticated analysis of the supply chain dynamic (especially under stress). To fully implement the more detailed methodology, further research would have to be conducted on several elements of the analysis approach, especially the supply chain response to external forces.

Both the high-level and more detailed level methodologies described in this report pose significant data acquisition issues. Some effort is required to provide a meaningful set of estimation parameters that best suit a particular type of network disruption. To the extent possible, local data should be used in developing estimates of disruption costs. The limited amount of extant data sources suggests that some effort also go into keeping track of such costs as an aid to future studies.

6.2 Future Research

This project has explored the feasibility of developing a high-level and a more detailed level methodology for assessing the economic impacts of disruptions to freight networks. The high-level methodology is intended to provide decisionmakers with "rules of thumb" that can be used to provide an estimate, often in the short term, of what the economic impact of disruptions might be. The high-level methodology holds promise for indicating which types of economic impacts are likely to be most important for different types of disruptions. It would be very useful to further develop this approach in spreadsheet format for different types of disruptions that could provide more illustration of how the methodology could be employed. Clearly, the more detailed methodology would require a greater level of effort in developing at sufficient detail and at much higher levels of analysis to estimate adequately a finer level of detail in terms of economic impact.

In addition to developing both the high-level and more detailed methodology, the following potential research topics result from this project:

- Figures 3-2 to 3-6 describe the major components of the more detailed impact methodology. Of these different components, the supply chain response analysis effort (shown in Figure 3-4) is in most need of research. As was shown in earlier sections of this report, many models exist for estimating economic impacts, some of which are used regularly in economic studies. However, this research has shown that analysis and modeling efforts of the supply chain response phenomenon have not been well developed. Part of this research would be to gain a better understanding of market responses to supply chain disruption. This is an area of research that deserves significant attention.

- Transportation network resiliency is one of the most important aspects of determining the ultimate economic impact of a disruption. The degree to which a network can bounce back from a disruption is directly related to the level of short-term economic impact. If a rail line that is disrupted can be restored or traffic diverted in a short period of time, the economic impact is likely to be not as great as a disrupted line that causes weeks of delay. The concept of resiliency, and how it relates to economic impact and the strategies for incorporating resiliency in networks, is an important topic in the broader investigation of economic impacts of network disruptions.
- Related to the previous topic, research would be useful in identifying the costs and benefits of different public policies to enhance security and resiliency of freight networks. What policies make the most sense given the different magnitudes of economic costs to likely disruptions? What are the benefits of implementing such policies? What are the costs associated with this implementation?
- It was difficult to identify the longer term changes that disruptions cause in production and location decisions. For example, the 2011 tsunami in Japan and the 2011 floods in Thailand have resulted in manufacturers of both automobiles and computers re-thinking the location of some of their production facilities. Very little research has been conducted on such cause-effect relationships between disruptions and location of economic activity. This could be coupled with an analysis of the longer term impact of such changes on U.S. gateways.
- The 3PLs are important actors in the supply chain, controlling much of the freight supply chain activity. The bigger 3PLs must deal with large numbers of carriers, shippers, and brokers. Very little information was found relating to the role of 3PLs in large-scale disruptions. How do they cope with cargo reassignments on a potentially vast scale?

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Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation