AN ANALYSIS OF METHODOLOGIES TO ESTIMATE THE ECONOMIC IMPACTS OF FREIGHT TRANSPORTATION SYSTEM DISRUPTIONS

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Andrew Vischio

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AN ANALYSIS OF METHODOLOGIES TO ESTIMATE THE ECONOMIC IMPACTS OF FREIGHT TRANSPORTATION SYSTEM DISRUPTIONS

Approved by:

Dr. Michael D. Meyer, Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Frank Southworth
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Laurie A. Garrow
School of Civil and Environmental Engineering
Georgia Institute of Technology

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LIST OF SYMBOLS AND ABBREVIATIONS

ATRI	American Transportation Research Institute
CIP/DSS	Critical Infrastructure Protection Decision Support System
CFS	Commodity Flow Survey
CGE	Computable General Equilibrium
DIETT	Disruption Impact Estimating Tool – Transportation
DOT	Department of Transportation
FPM	Freight Performance Measures Tools
GDP	Gross Domestic Product
I-O	Input-Output
LIFT	Long – Term Interindustry Forecasting Tool
MPO	Metropolitan Planning Organization
NAICS	North American Industry Classification System
NIEMO	National Interstate Economic Model
SCGE	Spatial Computable General Equilibrium
SCM	Supply Chain Management
SCPM	Southern California Planning Model

SUMMARY

The movement of goods is a large percentage of the economy and disruptions to this flow are extremely costly on every scale, yet there is no formalized process for studying these events and the effects they have on the economy. When a significant event occurs, such as a devastating hurricane or earthquake, there are usually multiple attempts, using different methods to estimate its effect on the economy. This leads to, as it did in the case of the 2002 shutdown of the Los Angeles and Long Beach ports, a series of reports that either support or try to discount previous estimation efforts. This practice seems to be counter-productive and a misallocation of resources.

A disruption will be costly to the economy, but estimating how far these costs propagate is a difficult task. Calculating the economic impact of a freight disruption is not just the increased cost in shipping goods, but a combination of this increase in cost and the impact reliable freight movement has on every other sector of the economy. Because these connections are numerous and complicated, a number of methodologies have been developed to estimate a quantitative value. Calculating this cost is important so that decisions to improve the freight system, whether they are physical or strategic improvements, are prioritized in a reasoned and systematic way.

The purpose of this research is to synthesize this knowledge in order to enable public entities to make more informed disruption policy, regulation and infrastructure investment and for private entities to plan for more resilient supply chains. This research shows how many different approaches can be taken when studying the economic impacts of similar disruptive events and conceptualizes the link between the supply chains, disruptions and their economic impacts.

CHAPTER 1

INTRODUCTION

1.1 Study Overview

Freight transportation is a $1.2 billion industry that generates eight percent of jobs and accounts for nine percent of the U.S. economy. These shares will only increase as projections show future trade increasing faster than the economy as a whole [1]. Supply chains are responsible for the movement and storage of raw materials, inventory, and finished goods from point of production to point of consumption. A series of innovations from containerization in the 1950's and 60's, to larger ships, to new information tools and outsourcing have undoubtedly enabled supply chains to increase their efficiency. However, this increased efficiency has not come without the drawback of supply chains becoming more complex and more vulnerable to turbulence. Some factors that contribute to potential supply chain disruptions include globalized supply chains, specialized factories, centralized distribution, reduced supplier base and increased volatility of demand [2]. This is a particularly disturbing trend considering a recent analysis of 600 companies that showed their average shareholder value plummeted after experiencing a supply chain disruption [3].

A comprehensive knowledge of supply chain and freight movement behavior is crucial given the importance of a fully functioning goods movement system. Clearly a disruption will be costly to the economy, but to what extent is a more difficult question. Calculating the economic impact of a freight disruption is not just the increased cost in shipping goods, but a combination of this increase in cost and the impact reliable freight movement has on every other sector of the economy. Because these connections are numerous and complicated a number of methodologies have been developed to estimate a quantitative value. Calculating this cost is important so that decisions to improve the freight system, whether they are physical or tactical improvements, are prioritized in a reasonable and systematic way. The purpose of this research is to synthesize this knowledge in order to enable public entities to make more informed disruption policy, regulation and infrastructure investment and for private entities to plan for more resilient supply chains.

This thesis is organized in the following way. Chapter 2 provides background information, recent developments, and a conceptual framework which will serve as a point of departure for examining the linkage between the supply chains, disruptions and their economic impacts. Chapter 3 presents a review of selected economic impact methodologies. Chapter 4 presents case studies which are used to illustrate the differences between methodologies and their relative merits. Chapter 5 discusses how the private and public sectors view and analyze freight disruptions, and Chapter 6 provides conclusions, recommendations and future research objectives.

CHAPTER 2

BACKGROUND AND CONCEPTUAL FRAMEWORK

This chapter will provide background information, a discussion of recent developments, and a conceptual framework which will serve as a point of departure for examining the linkage between the supply chains, disruptions and their economic impacts. In addition to these tasks, a discussion of supply chain visualization will provide insight into the development of the conceptual framework that will guide this analysis.

2.1 Defining Disruption

This effort to define freight disruptions will begin with an explanation of what freight disruptions are not. The freight disruptions that will be discussed in this report are not caused by congestion. Congestion regularly occurs on nearly every roadway, highway and interstate throughout the country. It is a topic that has been extensively studied, particularly by the Texas Transportation Institute. Congestion is caused by more people and freight using the system than can be handled [4]. A disruption to the freight transportation system, on the other hand, "is an event that interrupts the material flows in the supply chain, resulting in an abrupt cessation of the movement of goods. It can be caused by a natural disaster, labor dispute, dependence on a single supplier, supplier bankruptcy, terrorism, war, and political instability" [5]. Not included in this definition, but also a cause of freight disruptions are infrastructure failures, such as bridge failures and train derailments. The economic impacts of these types of disruptions tend to be more far-reaching, both in economic and spatial magnitude, than regular delays.

By definition, these events occur irregularly and have extremely variable consequences. One example of a freight disruption could be a shutdown at a port caused by a labor dispute. This famously occurred in 2002 at the Los Angeles – Long Beach twin ports in California. It most recently occurred on September 28, 2010 at the Port of New York and New Jersey [6]. An event like this has serious economic effects on private firms and the government, local economies and a nation's economy. Knowing, or estimating, these economic effects is important so that private firms and government agencies can make decisions regarding how much resources should be spent on mitigating or preventing these disruptions. Multiple methodologies have been developed to accomplish the task of estimating these complex economic figures.

2.2 Recent Trends

The causes of disruptions mentioned in the definition are natural disasters, terrorism activities, infrastructure failures and labor issues. As was mentioned before, the occurrence of these events is unpredictable. However, recent developments suggest that certain types of natural disasters may be occurring with increased frequency and intensity. This scenario could potentially have an impact on certain vulnerable infrastructure elements and in turn lead to more attention being given to disruption mitigation.

The Committee on Climate Change and U.S. Transportation Division on Earth and Life Studies of the Transportation Research Board reported in 2008 that there is a greater than 90 percent probability that intense precipitation events will continue to become more frequent and a 66 percent probability that there will be increases in hurricane intensity [7]. This report goes on to postulate that these more frequent severe events could cause inundation of roads, rail lines and airport runways in coastal areas and more frequent or severe flooding of low-lying infrastructure. It should not be overlooked, however, that this report explicitly states that that little consensus exists among transportation professionals regarding these issues. Whether or not these hypotheses hold true is unknown. However, if consensus shifts and more actions are taken to fortify supposed vulnerable infrastructure elements, economic impact studies can provide estimates to inform decision-makers that are prioritizing mitigation efforts.

While transportation system dependent companies are not faulted for things like natural disasters or terrorist activities causing abrupt disruptions, they can be held accountable for strategies and procedures that increase the magnitude of disruption impacts and lead them towards vulnerable positions. Examples of these types of strategies include just-in-time delivery and outsourced manufacturing. These strategies are widely adopted and have enabled increases in supply chain efficiency [8]. However, they also make supply chains longer, more complex, and more vulnerable to turbulence [9]. Models that can estimate the economic impact of disruptions given the use of certain supply chain strategies are extremely useful for informing decisions to dynamically change supply chains in a competitive market.

2.3 Creating a Conceptual Framework

This chapter has established a definition for freight disruptions and introduced topics such as who these disruptions can affect, what may cause these disruptions to be particularly costly and how the economic impacts can be measured. To facilitate a more comprehensive study of these topics, a conceptual framework is offered, illustrating how different variables interact in the event of a disruption to cause economic impacts. The framework also illustrates the need for economic impact estimation, and the role these estimation methodologies play in the transportation planning process.

2.3.1 Supply Chain Visualization

The conceptual framework will consist of a supply chain element, disruption identification elements, economic impact estimation elements and impact mitigation elements. Since the supply chain has the largest influence on the structure of the framework, the discussion will begin with illustrating the supply chain and its components.

The way supply chains are visualized changes depending on both the party examining the supply chain and the reason that party is studying the supply chain. Changes are made so that different concepts that relate to supply chain behavior can be analyzed and eventually conveyed. Despite these changes, the main components and relationships of the supply chain remain the same. There are a series of points or echelons that represent entities in the supply chain. These echelons are tiers in a supply chain. Tiers are connected physically to allow for the flow of goods and information. These connections are visualized as a series of lines that connect different echelons.

A view of the supply chain that varies significantly from the traditional view is provided by the RAND Corporation. When discussing the organizations involved in a supply chain disruption, the linear depiction of the process provides little insight. However, a tiered view of the supply chain involving different theoretical layers that was developed in a RAND Corporation report helps with identifying the entities involved in each type of disruption. The logistics, transaction and oversight layers make up the three tiers. Ocean carriers, ports, truck carriers and rail carriers are examples of the logistics layer. Retailers and foreign suppliers can be found on the transactional layer. The highest layer, oversight, includes the Federal Trade Commission, the U.S. Coast Guard, U.S.

Department of Homeland Security and other similar organizations [10]. This visualization, seen in Figure 1, not only identifies the vast amount of stakeholders in a given supply chain, but the many types of interactions between these stakeholders. Identifying the stakeholders involved in disruptions and the complexity of their interactions shows the complications of the issue and emphasizes the necessity for all of the entities to have a coordinated plan that will efficiently alleviate the disruption.

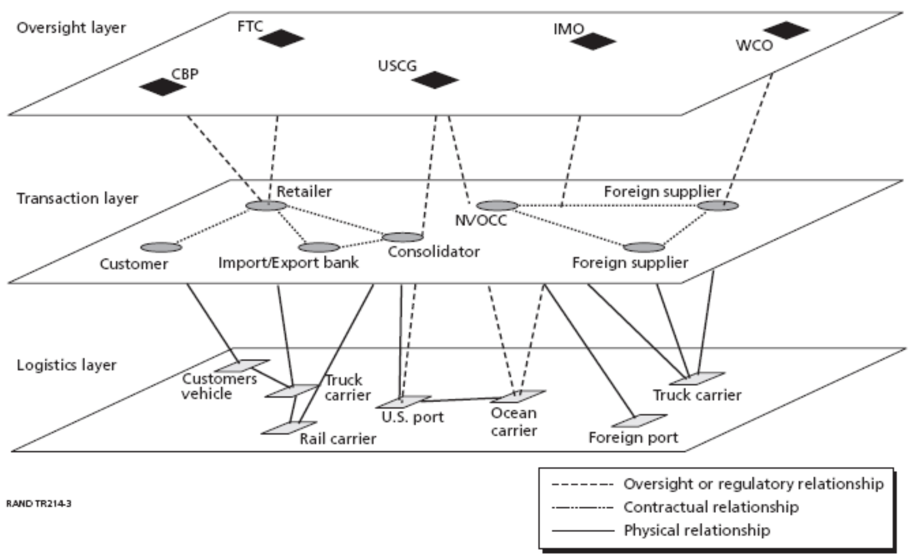

Figure 1: Supply Chain Layer Interactions [10]

This report also visualized a single layer in Figure 1, the logistics layer. The result of taking only this component is a representation of the supply chain that is much more standard and comparable to the traditional view. Figure 2 illustrates the movement of cargo in terms of the persons who have access to it (single-lined boxes) and by the places to which it travels (double-lined boxes and arrows). This representation has two objectives. One is to show the physical system or business side of the supply chain. The second is to indicate stages of the supply chain where access to the goods should be limited or monitored for security purposes.

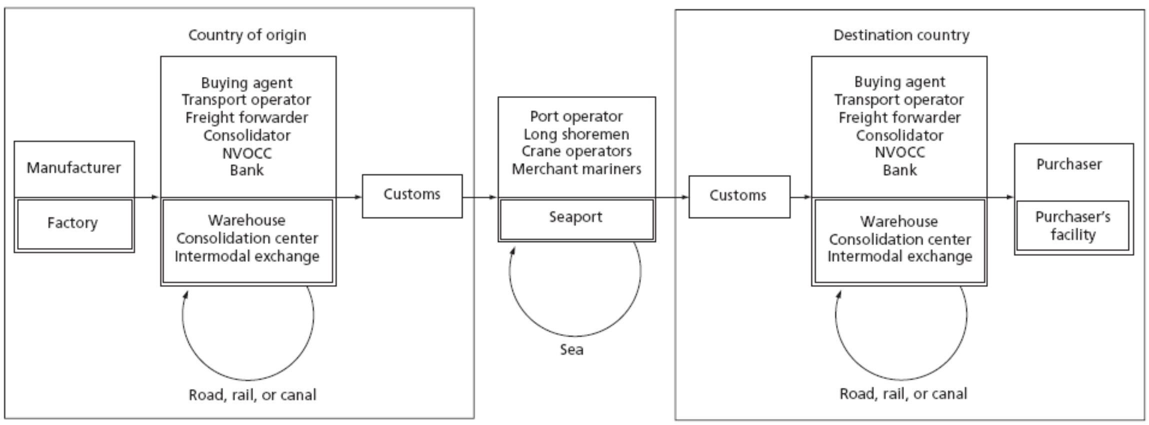

Figure 2: Supply Chain Logistics Layer [10]

Supply chains have also been visualized as a component of a larger framework. Figure 3 is included in a paper that studied disruption risks in supply chains with respect to the accidents in the U.S. Chemical Industry. In this visualization, the supply chain is part of a phased approach to disruption risk management that is used as a “funnel” to discover and quantify disruption hazards. In this situation, the depiction of the supply chain is simplified. This effectively emphasizes the other components of the framework and keeps the figure as understandable as possible.

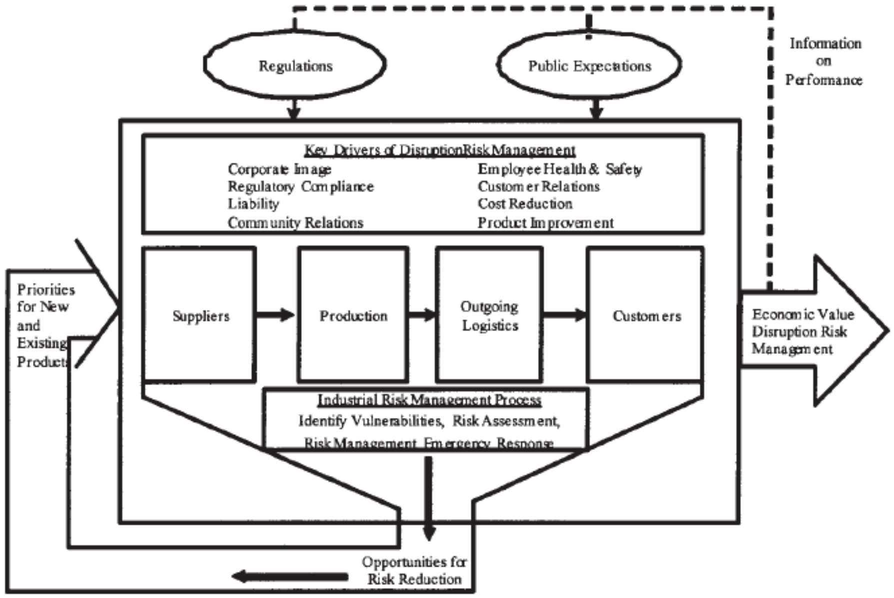

Figure 3: Risk Analysis and the Extended Supply Chain [11]

The following two figures are somewhat simplified, traditional representations of supply chains. The difference between the two figures is the flow of information. Figure 4 represents a supply chain with a traditional structure whereas Figure 5 depicts a supply chain with a flow of goods and information associated with a vendor managed inventory. In the traditional arrangement, demand information flows upstream, beginning with the customer. In a vendor managed inventory structure, both the tier 1 supplier and the retailer receive customer demand information [5].These supply chains were used in a report that examined how different supply chain structures would impact the effects of a disruption.

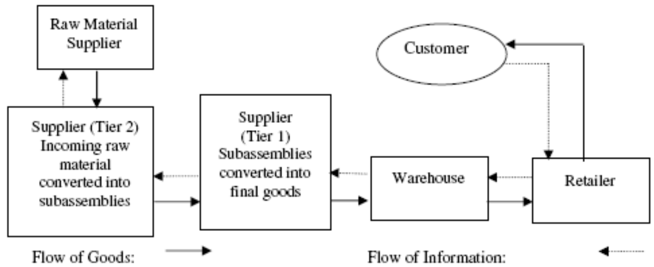

Figure 4: Flow of Goods and Information - Traditional Structure [5]

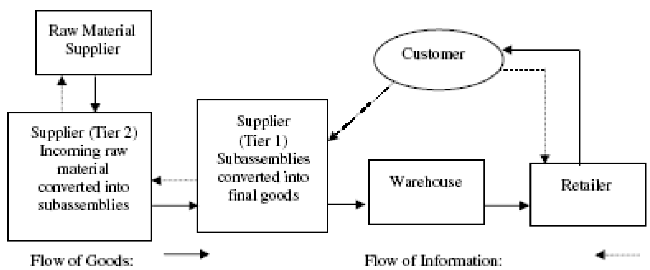

Figure 5: Flow of Goods and Information - Vendor Managed Inventory [5]

A further simplified visualization of the supply chain was used in a report which discussed why supply chain disruptions have received more attention in recent years and how supply chain structures can be used to mitigate negative effects. Central to the argument is that supply chains have become more “lean”, a strategy which calls for slimmed-down systems with little redundancy or slack. The two types of supply chain structures discussed are Hub-and-Spoke and Point-to-Point networks, shown in Figure 6 below. Because the report was examining the effects of lean systems and uncertainties, the supply chain has been depicted with shaded components which represent sites that hold inventory. The report goes on to discuss which structure is ideal given supply uncertainty or demand uncertainty.

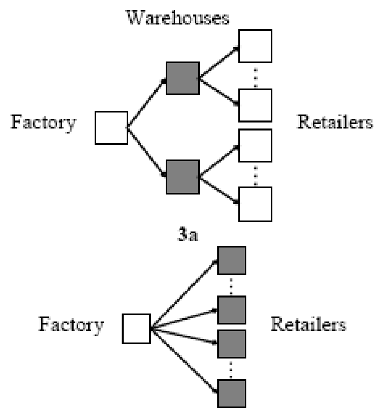

Figure 6: Hub-and-Spoke (above) vs. Point-to-Point Networks [12]

2.4 Framework Linking Supply Chains, Disruptions and Economic Impacts

As has been established, the traditional view of a supply chain is a linear connection of sectors that control the flow of goods and information[5], [1]. The links between these sectors are the transportation components of the supply chain. As can been seen in Figure 7, every form of transportation plays an important role, enabling the movement of raw or finished goods to their next destination. When the system works as intended, the freight movement sector drives a significant portion of the economy. In the event of an unexpected disruption, the effects could be significant and far-reaching [13]. A disruption to the freight system in effect prevents this transportation linkage from working at its full capacity. This conceptual framework helps illustrate the relationship between network performance, supply chain practices, government policies and how these variables affect economic impacts when disruptions in the transportation system occur.

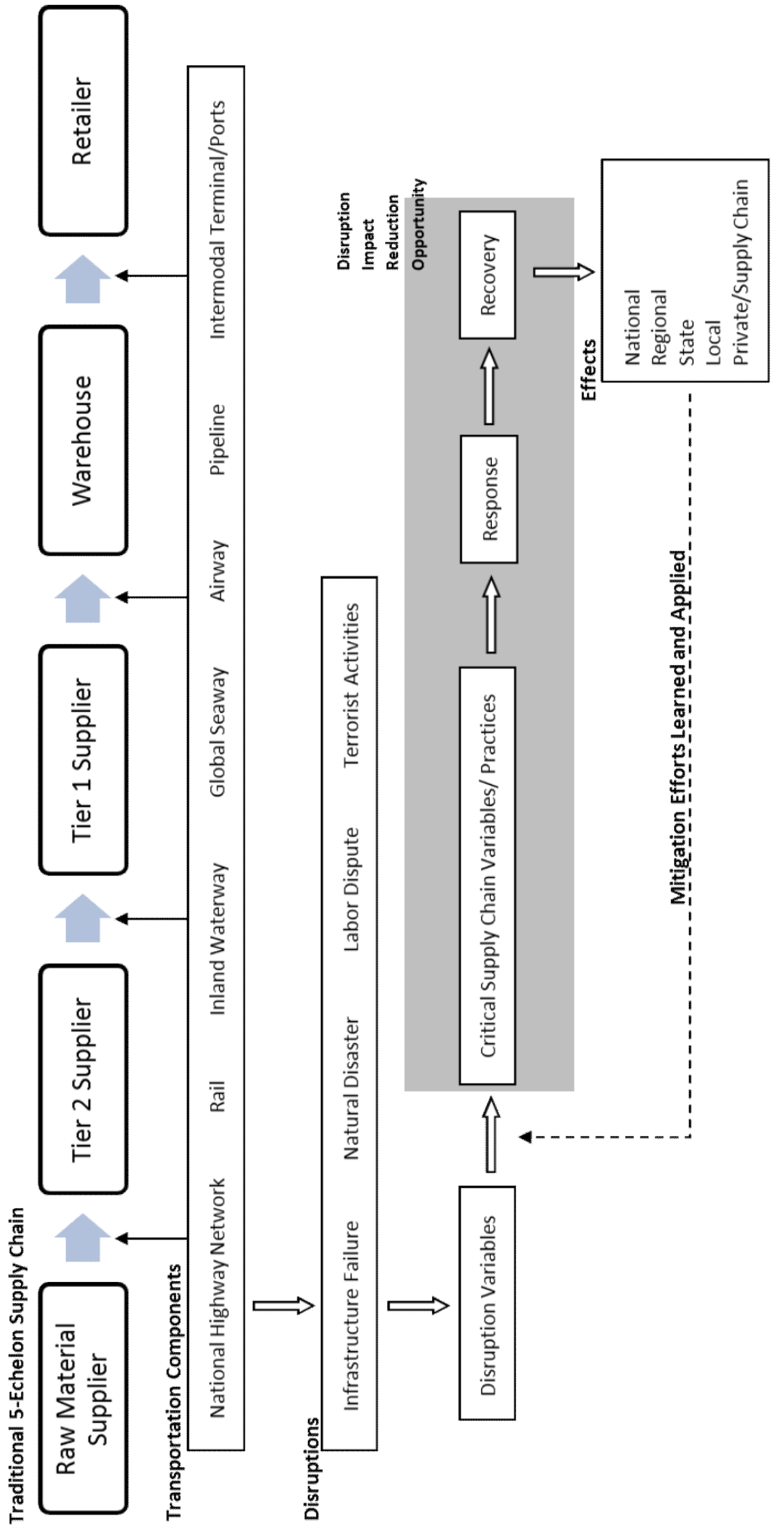

Figure 7: Supply Chain Disruption Impacts Conceptual Framework

The magnitude of a disruption's economic damage can generally be understood after identifying what the event was, the transportation components involved and the critical disruption variables in play. The most important driver of a disruption's economic impact tends to be the prominent, defining variables of the event. These would be listed in the disruption variables section. This is a broad category that can include the geographic location of the disruption, the length of the disruption, the importance of damaged infrastructure and the severity of the event. For example, the economic impact of a labor strike at a West Coast port depends heavily on the length of that disruption and the relative importance of the location of the disruption [14]. However, there are many studies that suggest that these important characteristics are not the only drivers of economic effects. Many different supply chain practices and infrastructure advances that could mitigate negative impacts have been studied. In this framework they are included as disruption impact reduction opportunities.

This framework indicates that these reduction opportunities, which fit into three categories, are specific decisions that can be used to lessen the negative effects of a chain disruption. In other words, this is the part of the supply chain disruption where stakeholders affected by the disruption can show resilience. The critical supply chain variables category focuses on attributes of a company's global supply chain environment that may amplify or mitigate the impact of disruptions [15]. The recovery and response categories focus on response plans after an incident, specifically ones that involve the recovery and reinforcement of freight systems through infrastructure investment or readjustment of supply chain dynamics.

The variables in the first category, critical supply chain variables, may include the location of suppliers, number of brokers, lead times, concentration of suppliers, workforce issues, customs regulations, storage requirements, product complexity and supplier manufacturing capacity. These are some of the examples that company executives have identified as having the potential to increase the difficult of disruption recovery [15]. Preemptive disruption-management strategies also fit in this category. These strategies, while specifically created to address the issue of a disruption, are put in place before the event and optimized even in the absence of a disruption ever occurring. These include inventory mitigation, sourcing mitigation or contingency rerouting [16].

The second and third categories are where post event recovery and response occurs in order to re-fortify the system and repair freight movement systems. These actions and plans can take place or be created by government entities or private firms. It would seem logical that both sectors would be invested in establishing these actions given the potential for a disruption to have immense economic impact and reach. Some examples of recovery and response items in the private sector include supply chain redesign, risk management centers, and expediting and premium freight [15]. Government responses can include plans from different levels of government and agencies. A customized state freight resilience plan that specifically deals with goods movement would be found in this category [17]. A state DOT freight recovery plan, although not widely established throughout the country, would certainly fit in this category. On the federal level, there are the National Incident Management System and the National Response Plan. These do fall under this category, but their lack of emphasis on the freight system recovery’s importance to economic recovery has been put into question [17].

Estimating the economic effects of a disruption is crucial to accurately identify critical infrastructure, but it is not a simple task. Not only are there many different methodologies to tabulate the effects, but then there is the question of what type of effect or scale to focus on. There have been studies that approach the task from a firm and local business vantage like Boarnet’s “Business Losses, Transportation Damage and the Northridge Earthquake” [19]. On the opposite end of the spectrum, container shipment delays into West Coast ports have been examined based on their effect on the national economy alone [8]. Other reports have approached the question of economic impact more comprehensively by estimating the impacts for every economic level, be it macroscopic or microscopic [18].

The process of estimating these economic damages and discovering their extent lends itself well to a process of learning and improvement. This could be referred to as the feedback loop in the conceptual framework and can be accomplished in different ways. One could study the economic impacts of an event and then propose future actions like policy directives [19]. Other studies, rather than suggesting policy directives, suggest building complementary transportation elements to mitigate negative economic impacts [20]. Another common approach is to study hypothetical situations to find optimal solutions. Examples of this method include finding the best strategy when dealing with recurrent and disruption risks in a supply chain [21], and studying the impact of inventory management systems on the magnitude of disruption effects [5]. These two examples showed that given identical disruption scenarios, economic impacts could be reduced with different inventory and supplier strategies.

Throughout this paper, this conceptual framework will be revisited in order to provide a baseline of understanding for how the topics discussed, such as economic impact methodologies, resilience strategies and government policies, all relate to the efficient working of the freight system and the supply chains that manage it.

CHAPTER 3

REVIEW OF ECONOMIC IMPACT METHODOLOGIES

This chapter presents a review of select economic impact methodologies. This review will introduce the models and software currently being used to estimate economic impacts of freight disruptions. The assortment of methods will be categorized based on their shared underlying mathematical principles and data requirements. Focusing on these categories will allow for a more comprehensive comparison as most of models have different capabilities and strengths.

This chapter will also describe representative studies that have used the four disruption impact methodologies previously discussed. This is necessary because many of the models that will be discussed do not explicitly model freight flow disruptions. Rather, they generate estimates of indirect effects from the direct effects of disruptions. The discussion of these impact studies will help to further explain the capabilities of these models and further portray the task of estimating the economic impact of a disruption.

3.1 Overview of Impact Methodologies

Economic impact methodologies are crucial to the transportation planning process because they provide information about how much of an impact a disruption has had or can have. The values estimated by these methodologies can be used in cost-benefit analyses to inform decision-makers on how to spend limited infrastructure money [22]. They can be used by individual firms to make supply chain decisions regarding where to place warehouses or how to select suppliers [5]. They can also be used by the federal government to make homeland security decisions [23]. As would be expected by the considerable implications of the results of these studies, the field of disruption economic impact assessment is sizeable. Therefore, these methodologies will be classified to enable further discussion.

Economic impact methodologies can be categorized in a number of different ways. These can include the data required by the method, the outputs generated or the situations it can describe. The selection of methods described here will be categorized based on their underlying mathematical principles and data requirements. This knowledge represents the most significant way these methods differ. The major types of methods include input-output models, macroeconomic models, system dynamics models and primary data analysis.

3.1.1 Input-Output Models

Input-output modeling is one of the more commonly used and widely accepted methods for assessing the economic impacts of disruptive events. One of the reasons for its common use is that it provides a concise and accurate means for describing the relationships between the United States' industry sectors. [24]. Its acceptance perhaps stems from the fact that its theories have been established for centuries. Early forms of input-output tables were developed by Eighteenth century French authors. Input-output models are based on the notion that the production of output requires input [25]. Another reason it is so commonly used is because of its ability to be modified to represent many different economic scales. Input-output tables can be created to represent a city, state or country's economy.

For example, Ham, Kim and Boyce incorporated input-output relationships to estimate and evaluate the impacts of transportation network disruptions caused by a hypothesized catastrophic event, an earthquake in the New Madrid Seismic Zone located in the center of the United States [26]. Their model, which they refer to as an interregional commodity flow model, consists of a multi-regional input–output model of 13 industrial sectors producing a like number of commodities that are distributed over seven regions. The mean shipment length and total commodity flows by mode are estimated from the model and translated into a real dollar value, which is then used as a measure of economic impact. Since this study examines a hypothetical situation rather than an actual event, it able to compare several different scenarios. The five scenarios used in this study are different combinations of segments of interstates being closed. The findings may be used to identify critical sections of the network and analyze post-event reconstruction strategies.

The selection of input-output based models that will be compared include IMPLAN, a model developed by the Minnesota IMPLAN Group, the National Interstate Economic Model (NIEMO) developed by the National Center for Risk and Economic Analysis of Terrorism Events at the University of Southern California, the MARAD Port Kit developed by the U.S. DOT Maritime Administration and the Southern California Planning Model (SCPM) developed by the same team as NIEMO. Table 1 is provided to concisely describe each model and identify its features and capabilities.

Table 1: Input-Output Models

Tool/Software	IMPLAN[1]	NIEMO[2]	MARAD Port Kit[3]	SCPM[4]
Infrastructure Disruptions Modeled	None directly	None directly	Port	Highway
Direct Effects	No	No	Yes	Yes
Indirect Effects	Yes	Yes	Yes	Yes
Short Term Impacts (> 6months)	Yes	Yes	Yes	Yes
Long Term Impacts (< 6 months)	Yes	Yes	No	Yes
Data Required	Inputs in terms of revenue or employment	Commodity flow data	Port investment, policy	Demand losses in output and employment
Spatial Impact	local, state	Local, state, region, national	Port, local, state, region, national	Local, state
Supply Chain Level Analysis	No	No	No	No
Outputs Generated	Dollar losses, employment, taxes, personal income	Dollars losses, employment, GDP	Employment, dollar losses, taxes	Dollar losses of output and companion job losses
Developers	Private	Academic	Public	Academic

Source: [1] [27], [28], [29]
[2] [30], [31], [32], [33]
[3] [24], [34]
[4] [32], [29], [13], [28]

3.1.2 Macroeconomic Models

Another class of economic models focuses more on large scale macroeconomic principals of transportation [35]. Commonly known as computable general equilibrium (CGE) models, macroeconomic models are multi-market simulations based on the simultaneous optimizing behavior of individual consumers and firms in response to price signals, subject to economic account balances and resource constraints [36]. These models are often used to estimate the economic impact of a disruption to lifelines such as water or electric utilities in addition to being used for transportation disruption impact assessment. A basic difference between input-output models and macroeconomic models is that the macroeconomic model tends to underestimate the economic impact of a disaster whereas an I-O model generally results in an overestimation. This is because the macroeconomic model assumes optimal adjustments of all endogenous factors, while an I-O model has rigidly linear characteristics [37]. What makes macroeconomic models very useful is their ability to incorporate a transportation network model to add a spatial dimension into the impact estimates generated, though this is only available in some more advanced forms of I-O based models. When this dimension is added, the resulting model is sometimes called a spatial computable general equilibrium (SCGE) model. Given an event that causes a freight disruption, a SCGE model can provide decision-makers with spatial information regarding how far losses extend into each region because of intra and interregional trading disruption [38].

For example, Rose, Asay, Wei and Leung [33] estimated the economic impacts on the U.S. economy of a one-year halt in all imports from the rest of the world in response to an external threat to the U.S. using a macroeconomic model developed by Regional

Economic Models, Inc. called REMI. The case of such a shutdown was not specified, but suggestions of what could cause this situation include the threat of a terrorist attack or spread of a disease. The time frame of the disruptions modeled is three months, six months and one year. Different data and refinements were needed for various types of closures, which included shutdown of imports, shutdown of exports, shutdown of international travel and shutdown of immigration. Some of the data necessary for this estimation included industry sales, international exports for each sector, data on levels of tourism and total expenditure by international tourists within the United States and a regional breakdown of expenditure statistics. The results of this estimation showed that a complete shutdown of the U.S. borders, the most drastic of the situations modeled, and which prevented all movement of people and goods for one year, would cause a loss of GDP of about $1.4 trillion in 2006 dollars and a loss of more than 21 million jobs.

The selection of macroeconomic based models that will be compared include the Long-term Interindustry Forecasting Tool (LIFT) developed by Inforum, a nonprofit economic consulting group affiliated with the University of Maryland, the Regional Economic Models, Inc. (REMI) model and a spatial computable general equilibrium (SCGE) model which is not a tool, but rather a subset of models that fit into this category. Table 2 is provided to concisely describe each model and identify its key features and capabilities.

Table 2: Macroeconomic Models

Tool/Software	LIFT[1]	REMI[2]	SCGE[3]
Infrastructure Disruptions Modeled	None directly	None directly	Rail, highway
Direct Effects	No	No	Yes
Indirect Effects	Yes	Yes	No
Short Term Impacts (> 6months)	Yes	Yes	Yes
Long Term Impacts (< 6 months)	Yes	Yes	No
Data Required	Federal trade data	Policy variables, base year trade flow	Transportation network, interregional passenger and trade flow
Spatial Impact	National	State, region	Local, regional
Supply Chain Level Analysis	No	No	No
Outputs Generated	GDP change	Employment, GDP, personal income	Dollar losses
Developers	Academic	Private	Academic

Source: 1 [39], [8]
2 [40], [33]
3 [25], [38], [37]

3.1.3 System Dynamics Models

System dynamics models, as the name implies, never achieve a state of equilibrium like input-output models do. This may be a more accurate method considering the complex progression of infrastructure utilization in the event of a disruption. The structure of system dynamics models includes time varying feedback loops and time delays that affect the behavior of the entire system. This structure differentiates system dynamics from I-O and CGE methodologies. Feedback loops, stocks and flows help to capture the nonlinearity of a system using the relationships of the components as the basis of the model [41]. System dynamics models are versatile in that they can estimate a disruption's impact on a small scale, like a single supply chain, or a larger scale, like the impact on an entire region's economy. Models that estimate on the scale of a supply chain may include system elements like warehouse inventory and customer demand, whereas models that operate on a higher level would be more interested in relationships such as the link between the infrastructure and the banking sectors.

Dauelsberg and Outkin [43] present a model of impacts arising from disruptions to critical infrastructures. The model they present is a component of the Critical Infrastructure Protection Decision Support System (CIP/DSS) which simulates the dynamics of a set of interconnected individual infrastructures. The results from a disruption due to an infectious disease outbreak are presented as an illustrative example of the capabilities of the model. The dynamic nature of this model allows for disruptions and, with the help of an additional economic model, their economic consequences to be modeled as non-equilibrium events where the interdependent nature of various infrastructures allows event and disruption propagation from one infrastructure to another. In this model, lost value-added, lost sales, and lost wages for each of the North American Industry Classification System (NAICS) supersectors are calculated to estimate these economic impacts to the economy.

The selection of system dynamics based models that will be compared include the iThink developed by isee Systems and the Critical Infrastructure Protection Decision Support System (CIP/DSS) developed at the metropolitan level by the Los Alamos National Laboratory and at the national level by Sandia National Laboratories. Table 3 is provided to describe each model and identify its key features and capabilities.

Table 3: System Dynamics Models

Tool/Software	iThink[1]	CIP/DSS[2]
Infrastructure Disruptions Modeled	None directly, supply chain only	Nation's critical infrastructure, i.e. bridges, highways, tunnels, railroads
Direct Effects	No	No
Indirect Effects	No	No
Short Term Impacts (> 6months)	Yes	Yes
Long Term Impacts (< 6 months)	Yes	Yes
Data Required	Supply chain structure and relationships	Supply chain structure and relationships
Spatial Impact	Firm	Firm, local, national
Supply Chain Level Analysis	Yes	Yes
Outputs Generated	Inventory level, goods in transit, unfilled orders	Decision maps
Developers	Private	Public

Source: [1] [5], [42]
[2] [43], [44]

3.1.4 Primary Data Analysis

Primary data can be collected through questionnaire, interview, and telephone surveys. In general, disruption impact economic estimations based on primary data are more applicable to direct loss estimation and are better suited to evaluate losses after they have taken place [22]. Generating estimates of disruption economic impact using surveys could have a line of questioning regarding business losses, business losses attributed to transportation damage, the severity of a number of transportation and non-transportation impacts, and a company's response to the transportation damage [19]. Another way to generate estimates of disruption economic impact that falls in this category are methodologies that combine qualitative evaluation with interviews and expert input in brainstorming "sessions" [45].

Tierney used primary data analysis to study business vulnerability and disruption experienced during the 1993 Midwest Floods [46]. This paper presents preliminary findings from a study of a random sample of 1079 businesses in Des Moines/Polk County, Iowa, a community that experienced extensive damage and disruption as a result of the 1993 floods. The primary data was collected using a two-stage stratified sampling method that selected businesses for surveys in Des Moines/Polk County. The stratifying variables were business type and business size. The initial mailing of questionnaires was then followed up by telephone calls. Survey question answers regarding disruption of lifeline services, business losses, preparedness and other business activity responses. Qualitative analysis performed on the data estimated extent and duration of lifeline service interruptions, disruptiveness of lifeline outages and percent business closure.

Table 4 is provided to concisely describe this model and identify its key features and capabilities.

Table 4: Primary Data Analysis

Tool/Software	**Survey, Interview[1]**
Infrastructure Disruptions Modeled	n/a
Direct Effects	Yes
Indirect Effects	No
Short Term Impacts (> 6months)	Yes
Long Term Impacts (< 6 months)	Yes
Data Required	Surveys, interviews, expert analysis
Spatial Impact	Local
Supply Chain Level Analysis	No
Outputs Generated	Self-reported data
Developers	N/A
Source: [1] [22]	

3.1.5 Conceptual Framework – Organizing Concept

This chapter presented a review of select economic impact methodologies that introduced the models and software currently being used to estimate economic impacts of freight disruptions. As the discussion indicated, these methodologies are used by either or both private firms and government agencies. Figure 8 shows where these methodologies fit within the context of the conceptual framework. These methodologies are used to generate estimates of the economic impacts of disruptive events. These estimates are then analyzed in order to improve the freight transportation system or supply chain structure. The results of this analysis inform resilience measures via a feedback look. Without these estimations, resiliency measures for supply chains and the transportation network that supports them would be misinformed or impossible.

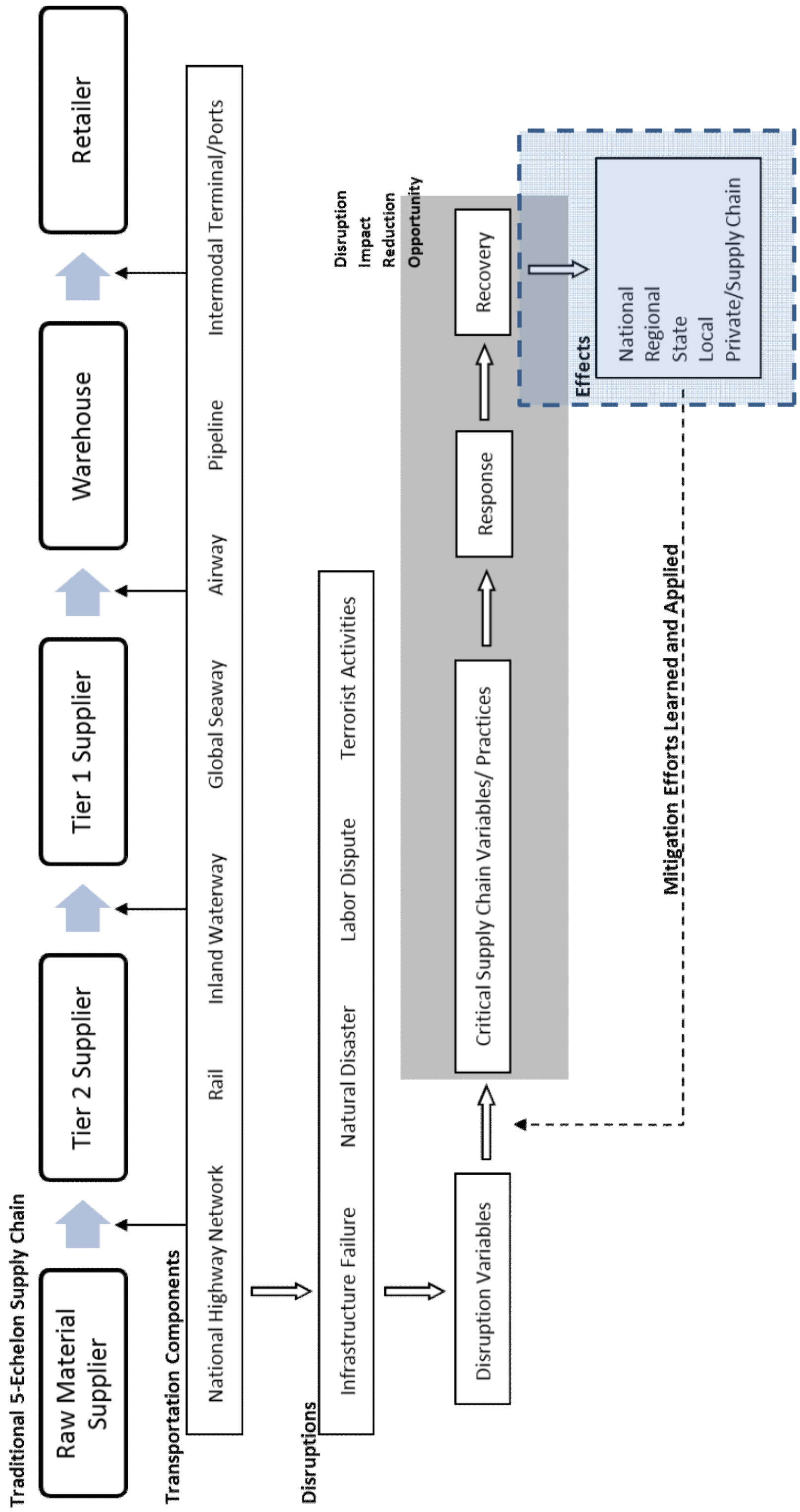

Figure 8: Conceptual Framework Impact Estimation Methodologies

CHAPTER 4

CASE STUDIES

This chapter describes a theoretical framework for analyzing efforts to estimate the economic impact of disruptions to the freight transportation system. Many of the principles in this framework are based on research priorities in hazard lost estimation identified by Rose [22]. This theoretical framework will be tested by examples of economic impact estimation efforts focused on different types of transportation system disruptions. Additionally, two examples of similar disruption studies will be compared in each case study to show how different approaches can be taken to estimate the economic effects of similar situations. Information in this chapter regarding the estimation methodologies and the events being studied is based on a literature review. The objective of this analysis is not to prove one method superior, but rather to illustrate and propose reasons why there are many different approaches than can be taken when studying the economic impacts of very similar events.

4.1 Analytical Framework

A framework for analyzing economic impact estimation efforts can be divided into seven functional characteristics:

1. Spatial context
2. Temporal context
3. Distributional impacts
4. Direct and high-order effects
5. Data required and ability to replicate
6. Economic indicators

7. Visualization potential

4.1.1 Spatial Context

The spatial context of the impact estimation refers to the methodology's ability to delineate the effects on the scale of a private firm, local, state, region or nation. This is an important aspect of the estimate as disruptions often affect infrastructure that is critical to economies not directly impact by the original occurrence [41]. The ability of a methodology to represent effects in a broad spatial context may prove to be very critical in the future if transportation infrastructure investment continues to focus on a megaregion concept. The connectivity of regions and access to nearby cities is one of the central ideas behind megaregion theory [47]. Megaregions are already responsible for a disproportionate amount of the United States' economy based on land area. Additional development at the megaregion scale will only increase the importance of freight's ability to move efficiently within these areas.

4.1.2 Temporal Context

The effects of a disruption are difficult to determine immediately after the event in that both short term and long term effects are important. However, it is often the case that short term effects of a disruption are misleading. There have been instances where, in the wake of a significant disruption, an economic surge in certain beneficiary industries masks the long term negative effects of the event [19]. The ability of a methodology to capture both short term and long term effects increases the accuracy of the estimation process. For the purpose of this analysis, short term effects will be limited to periods less than six months after the disruption.

4.1.3 Distributional Impacts

Distributional impacts refer to an economic impact methodology's ability to disaggregate the economic effects of a disruption by sector, industry, or some other grouping. This is beneficial for two major reasons. The first is that the ability to identify certain sectors or industries as the most susceptible to negative economic impacts increases the number of stakeholders who may not be aware of their vulnerability. This capability also provides data that could show what party should reasonably be expected to invest in preventative measures.

4.1.4 Direct and High-Order Effects

Direct, indirect and induced effects are terms that are often discussed in the impact estimation literature, but do not have exact definitions. Direct effects of a disruption are property damage or on-site business interruption caused by the disruption itself. Indirect effects are derived, ripple or multiplier impacts on a regional or national economy. Induced effects are generally the economic impacts generated by tertiary results like employee spending. For the sake of continuity and ease of comparison, these impacts can be reduced to direct and high-order effects, with high-order effects incorporating both indirect and induced effects [22]. In more cases than not, the costs to the transportation system component affected will be less than the costs to the entire economy. It is important for a methodology to incorporate both of these effects.

4.1.5 Data Required and Ability to Replicate Effort

Different methodologies require an assortment of data as the baseline for estimating economic impact estimates. Some data is free, in the public realm and easy to acquire. Other data is costly requires effort to acquire and may have proprietary or nondisclosure limitations. While the accuracy of estimates is ultimately most important, the ability of the data and methodology to be acquired and repeatedly used for different events cannot be overlooked. The more straightforward the data collection and analysis is, the greater the possibility of using the same methodology to analyze similar disruptions across the country.

4.1.6 Economic Outputs

There are multiple ways to describe the economic impact of a transportation disruption. The most common are in actual dollars, percent of national or regional GDP, or in the currency of the country where the estimate takes place. Effects could also be shown in labor-hours or jobs. Depending on the political climate, a severe reduction in jobs may prove to be of most concern to the general public and decision-makers.

4.1.7 Visual Potential

The ultimate goal of economic impact estimates is to provide a reasonable estimate of the effects of transportation disruptions on the freight system. If these estimates prove to be significantly debilitating to an economy, actions should be taken to prevent or reduce such effects. An easy way to build a consensus, in addition to providing accurate results, is to provide results that are easy to comprehend. Visuals depicting a study's findings often resonate better with audiences than raw data.

4.2 Case Study: Interstate Highway Closures

The development of the interstate system in the United States is arguably the most significant infrastructure achievement in U.S. history. It enables the current U.S. lifestyle by allowing people and goods to travel large distances extremely efficiently. Chapter 2 of this paper discusses some specific figures that express highway freight's importance to the U.S. economy. Interstate highways are susceptible to regular delays caused by congestion, especially in heavily used corridors. However, this report is only concerned with the economic effects of unexpected disruptions. Disruptions to the interstate highway system are most likely caused by infrastructure failures or natural disasters. The two events that will be analyzed in this case study are caused by natural disasters: storm-related closures of Interstate 5 and Interstate 90 in Washington State, and a series of rockslides closing Interstate 40 near the North Carolina-Tennessee border. The Washington State disruption study was undertaken by the Washington State Department of Transportation and Washington State University [20]. The I-40 disruption study was undertaken by the American Transportation Research Institute (ATRI) [48].

Many economic impact studies are conducted on hypothetical scenarios to assist transportation planning. Both of these events, however, did occur and were studied after the event's conclusion. The storm-related closures of Interstate 5 and Interstate 90 in Washington State occurred in the winters of 2007 and 2008, respectively. Both closures lasted four days, with I-5 being closed because of floods and I-90 being closed for avalanche control. Both eventually reopened at full capacity at the end of the four day event. During the disruption, detour routes that lengthened trips had to be used [20]. The series of rockslides closing Interstate 40 near the North Carolina-Tennessee border for nearly six months occurred in late 2009 and early 2010. The involved portion of the interstate eventually reopened at full capacity, but during the event detour routes that lengthened trips had to be used [48].

4.2.1 Analysis

The methodology to estimate the economic impact of the I-5 and I- 90 disruptions in Washington State involves a combination of primary data analysis and an input-output model called IMPLAN. The methodology to estimate the impact of rockslides closing Interstate 40 near the North Carolina-Tennessee border uses Federal Highway Administration's Freight Performance Measures program tools. While this methodology did not generate economic impacts, it provides Freight Performance Measures data and a framework for estimating economic impact data from these measures. Using this suggested method, the eventual methodology could be categorized as a macroeconomic and transportation network model.

The spatial context of both of these studies is somewhat different. The study on the I-5 and I- 90 disruptions in Washington State focuses on the impacts to the state and the local regions within the state. The reason for this is "the study's researchers were not able to correlate databases for out-of-state truck owners with in-state databases without significant reprogramming" [20]. The ATRI I-40 disruption study does not explicitly calculate economic effects, but rather generates data that could be using toward calculating these effects. The most direct use of this data would be to calculate total hours of delay and increases in operational costs for the firms that operate on that route. Calculating the economic effects on any larger scale would require more data and an additional economic impact model.

The statewide economic impacts of the Washington State disruptions are estimated for a year after the four day disruptions. Therefore, the results from this estimate can be categorized as long term effects. The ATRI I-40 study compares truck flow characteristics during the disruption while drivers were using alternate routes to truck flow characteristics during a control period when there was no disruption. Without incorporating any additional data, this information could be translated into only short term effects.

There is a significant difference in the extent of distributional impacts between these two estimation studies. The economic impacts of the Washington State disruptions are estimated and disaggregated by the trucking industry; freight-dependent industry sectors, including agribusiness, forest and wood products, construction, manufacturing, wholesale, retail; types of commodities shipped; and all other economic sectors. The impacts generated by the ATRI I-40 disruption study do not have the potential to be disaggregated any further than the trucking industry without additional data sets.

These two methods derive a different range of effects. Direct, indirect, and induced business losses of the Washington State disruptions are estimated, meaning both direct and high-order effects are included. The impacts generated with data provided by the ATRI I-40 disruption study would only be for freight-dependent industries and therefore only direct effects.

Data required and ability to replicate the analysis is an instance where these two methodologies shift strengths. The primary data analysis requires a total of 2,758 direct surveys of trucking firms and companies with private fleets. The input-output analysis requires inputs in terms of revenue so, “additional costs incurred both during and after the road closures were converted into revenue changes based on the price elasticity of truck transportation” [20]. This would be a difficult methodology to repeat in a different part of the country with a similar scenario because of the use of a state specific input-output model and time and labor intensive surveying efforts. The ATRI I-40 disruption study generates data to be used in a future effort to estimate economic impacts, so technically this data would be the required data in another methodology. The Freight Performance Measures data can be easily gathered for different highways and different areas of the country, so it would be a relatively simple task to repeat this process elsewhere.

The study on I-40 does not show the potential for generating a large amount of economic outputs. The Washington State study reports total lost dollar output, employment loss, state tax revenue loss, and reduction in personal income. The ATRI I-40 disruption study suggests that the data could easily be used to estimate trucking industry losses.

The area where the ATRA study stands out is in visualization. The Washington State study provides no visualizations for the economic impacts aside from standard figures and tables. The ATRI study, conversely, uses detailed maps depicting changes in freight flow and truck speed characteristics that would nicely complement future economic impact studies. It would be easy to recognize why certain areas or trucking routes experienced impacts if these visuals were to be used in tandem with economic estimates.

4.2.2 Summary Table

Table 5: Interstate Highway Case Study Summary

Interstate Highway Case Study - Disruption Impact Methodology Summary		
	I-5 and I-90 Washington State	**I-40 North Carolina - Tennessee**
Methodology	I-O (IMPLAN) and primary data	Component of macroeconomic/ network model (FPM)
Spatial Context	State and regions within state	Potential for firm level
Temporal Context	Long term	Short term
Distributional Impacts	Highly disaggregated	No distributional impacts
Direct and High-Order	Direct and high-order	Direct
Data and Replication	Difficult to obtain, hard to replicate (individual surveys)	N/A, easy to replicate
Economic Output	Dollar losses, employment, state tax, personal income	Potential to convert into trucking industry losses
Visualization Potential	None	Clear and informative

4.3 Case Study: Los Angeles Long Beach Port Shutdown

Trade activity, in terms of imports and exports, accounts for 20 percent of the United States economy, and has been one of the fastest growing sectors of the economy for several decades [49]. Not surprisingly, given its size and location, California ports have handled a large percentage of this increase. As of 2000, California ports handle over 20 percent of the value of all U.S. trade [14]. Ports, especially those that have a high profile and are heavily used, are susceptible to delays caused by terrorist activities, natural disasters and labor disputes. The two events that will be analyzed in this case study are the 2002 shutdown of the Los Angeles – Long Beach ports caused by a labor dispute and a hypothetical three year shutdown of the Los Angeles – Long beach ports coupled with a one week precautionary halt to all U.S. port activity. The 2002 shutdown economic impact study was performed by Park, Gordon, Moore II and Richardson and published in *Growth and Change* [31]. The three year shutdown economic impact study was performed by Arnold, Cammarata, Farmer, Kowalewski, Ladipo, Lasky, and Moore of the Congressional Budget Office of the U.S. Congress [8].

In some instances, a particularly disruptive event can spur interest in performing multiple economic impact studies on that event or potential similar events [50]. This is the case with the 2002 shutdown of the Los Angeles–Long Beach Ports. Since this event, many economic impact studies have been conducted on the economic impact of this labor strike and other hypothetical scenarios that would render the port inactive. Both scenarios in this case study involve a shutdown of the LA-Long Beach twin ports. The first is the real 11 day shutdown that occurred in 2002. The other is a hypothetical three year shutdown of the Los Angeles – Long beach ports coupled with a one week precautionary halt to all U.S. port activity with a share of those ports' former traffic being diverted to other ports.

The estimation of the economic impact of the 2002 shutdown uses an input-output model developed by the University of Southern California Homeland Security Center called the National Interstate Economic Model (NIEMO). The estimation of the economic impact of the three year hypothetical shutdown uses a model that combines input-output model and macroeconomic model properties called the Long-term Interindustry Forecasting Tool (LIFT) developed by Inforum.

4.3.1 Analysis

Regarding spatial context, the study of the 2002 shutdown estimates the economic impacts to cities in California, the state of California, multi-state regions and the rest of the 49 states on a state-by-state basis. The three year shutdown estimates the economic impacts on a national level without disaggregating the effects into smaller zones.

The framework to analyze these case studies could have been created to include a medium-term impact in addition to the short and long term impacts in the temporal context framework. Short and long terms were ultimately chosen because they were most common and it simplified the analysis. This is one instance where ambiguity remains. The study on the 2002 shutdown estimates the economic impacts up to four months after the shutdown. This can be categorized short term. The three year shutdown study is more complicated, in terms of temporal context, because there are two disruptions occurring in the scenario. One disruption is the three year shutdown and the other disruption is the precautionary shutdown of all U.S. port activity for a week. Because the LA-Long Beach twin ports are the subject of this case study, more focus will be placed on that estimate's characteristics. Since the shutdown in this scenario is three years, and the economic impact estimates are only for each three years of shutdown, this translates to long term impacts. Translating these yearly costs into daily costs, as this report does, is not the same as calculating short term impacts.

Distributional impacts were handled very differently by both of these impact studies. The economic impacts of the 2002 shutdown are estimated and disaggregated by 29 commodity sectors and 18 service sectors. Conversely, the three year shutdown study generates economic impacts that are not disaggregated by industry or economic sector. This could be the result of the report's target audience not requiring this additional information.

Direct impacts are estimated by the authors of the 2002 shutdown study whereas NIEMO was used to generate indirect impacts. For the purposes of this case study, the input-output methodology will only be credited with indirect or high-order effects. The impacts generated by the three year study, as would be expected by the high level of aggregation, are only high-order effects.

Both methodologies used in these studies require data that is fairly easy to acquire. However, the cost of this data is very different. The analysis of the 2002 shutdown study requires proprietary trade data to estimate the direct effects that were ultimately used in the NIEMO input-output analysis. This would not be an extremely difficult methodology to repeat in a different part of the country with a similar scenario because of the use of readily available data. However, since this data is proprietary, the effort may be somewhat cost intensive. The three year shutdown study requires data from the federal government, specifically the Foreign Trade Division of the Census Bureau and by the U.S. Maritime Administration, on imports arriving at individual ports by container and arriving nationwide by all modes of transportation. This data is available to the public and extremely detailed enabling this methodology to be repeated elsewhere.

Both estimation efforts provide basic metrics to report economic impact. The advantage of doing this is that the outputs are so easy to understand, so that the message conveyed is hard to complicate. The 2002 shutdown study reports economic impact in U.S. dollars. The three year shutdown study reports economic impact in real GDP reduction.

Unlike other economic impact models, the models used in these studies do not prioritize creating visualizations to accompany data outputs. Neither methodology creates figures or maps that are illustrative beyond typical tables and charts.

4.3.2 Summary Table

Table 6: Port of LA-Long Beach Case Study Summary

	2002 Shutdown	3 Year Shutdown
Methodology	I-O (NIEMO)	I-O and macroeconomic (LIFT)
Spatial Context	City, state, multi-state region, state-by-state	National
Temporal Context	Short term	Long term
Distributional Impacts	Highly disaggregated	No distributional impacts
Direct and High-Order	High-order	High-order
Data and Replication	Easy to obtain, potentially expensive, replicable	Easy to obtain, inexpensive, replicable
Economic Output	Dollar losses	GDP
Visualization Potential	None	None

4.4 Case Study: Railroad Disruption

Some estimates predict freight ton-miles in the United States will increase 35 percent by 2035. Trucks will carry the majority of this increase. However, railroads may carry up to 38 percent more freight than they do today [1]. Additionally, rail has been touted as being the more environmentally responsible alternative for freight movement. If there is legislation passed regarding climate change mitigation, rail stands to benefit greatly. Railroads, like highways, are vulnerable to disruptions caused by natural disasters and infrastructure failures. Furthermore, U.S. railroads are part of the Strategic Rail Corridor Network and carry U.S. Department of Defense shipments making them critical for national defense [41]. The two events that will be analyzed in this case study are the 1997 Union Pacific service disruptions and hypothetical Tokai-Tonankai earthquakes in Japan. The Union Pacific economic impact study was prepared by Weinstein and Clower for the Railroad Commission of Texas [51]. The hypothetical Tokai-Tonankai earthquakes economic impact study was prepared by Tsuchiya, Tatano and Okada and published in *Economic Systems Research* [37].

This case study analyzes disruptions that occur as a result of an infrastructure failure and a natural disaster. Because the Union Pacific service disruptions were caused by infrastructure failure, surrounding infrastructure, i.e. highways, are not disrupted. Conversely, hypothetical earthquakes in the Tokai-Tonankai region of Japan would affect both highways and railroads. This difference is part of the reason for using different economic impact methodologies.

4.4.1 Analysis

The methodology to estimate the economic impact of the 1997 Union Pacific service disruptions uses primary data analysis. A model called a spatial computable general equilibrium (SCGE) model, which has previously been categorized as macroeconomic model, is used to estimate the economic impacts of a hypothetical earthquake in the Tokai-Tonankai region of Japan.

A methodology that relies on primary data, such as surveys, does not lend itself well to economic impact studies that are spatially thorough. Also, the Union Pacific economic impact study was prepared for the Railroad Commission of Texas, so it is to be expected that it has a narrow spatial context that focuses on cities within Texas and the state as a whole. The hypothetical Tokai-Tonankai earthquakes economic impact study, although not in the United States, estimates both localized and inter-regional effects.

These two economic impact studies have different temporal objectives. The Union Pacific study reports losses seven months after the disruptions. This will be categorized as long term effects. The Tokai-Tonankai earthquakes study only reports impacts on a per day basis, so this will be marked as short term only. It appears possible to multiply these daily effects by a variable amount of days to capture long term effects, but that would not capture the market's dynamic response to the event.

Two distinct approaches are taken, with respect to distributional impacts, by these studies. The Union Pacific estimates are for multiple economic sectors whereas the Tokai-Tonankai earthquake estimates are only for the transportation sector. Though the Tokai-Tonankai estimates show the effects for multiple transportation modes, this is still only one sector of the economy. The Union Pacific study captures effects to the agriculture, paper and forest products, building materials, electric utilities and retail trade sectors.

Again, these studies take very different approaches regarding direct and indirect or high-order effects. The Union Pacific analysis only seeks to find what effect this transportation disruption has on the greater economy of Texas. In other words, the report only seeks high-order effects. The Tokai-Tonankai study only estimates transport related, direct impacts caused by this disruption. It does not estimate what high-order effects result from these transportation industry changes.

The Union Pacific economic impact study does not use complex models, but rather chooses to estimate values from surveys, industry specific sales trends and other primary data sources. The Tokai-Tonankai study requires interregional net passenger flow data, railroad and highway network information and trade flow data between the nine regions being examined. This is one instance where a methodology dependent on primary data may not be very difficult to repeat for different scenarios elsewhere. The Tokai-Tonankai data is from Japan, but there are readily available datasets from the U.S. federal government that would be able to be used in the SCGE model.

Both estimation efforts provide basic metrics to report economic impact. As was the case in previous case studies, the study's outputs are easy to understand, and the results shown are hard to misinterpret. The Union Pacific disruption study reports economic impact in U.S. dollars. The Tokai-Tonankai data reported data in Japanese yen.

Requiring transportation network data for the SCGE model enables the disruptions to be visualized, which allows for a straightforward understanding of why certain regions are affected more than others. The primary data analysis does not have these types of datasets, so visualization is very limited.

4.4.2 Summary Table

Table 7: Railroad Disruption Case Study Summary

	Union Pacific	**Tokai-Tonankai Earthquake**
Methodology	Primary data analysis	Macroeconomic (SCGE)
Spatial Context	City, state	Intra and interregional
Temporal Context	Long term	Short term
Distributional Impacts	Highly disaggregated	No distributional impacts
Direct and High-Order	High-order	Direct
Data and Replication	Easier to obtain than other primary data efforts, replicable	Easy to obtain, inexpensive, replicable
Economic Output	Dollar losses	Economic losses (yen)
Visualization Potential	None	Clear and informative figures

4.5 Case Study: Northridge Earthquake

The previous three case studies have focused on classes of infrastructure that have been disrupted. The types of infrastructure included highways, ports and railroads. This fourth case study will shift slightly from this approach and analyze methodologies used to estimate the economic impacts of a specific natural disaster, inclusive of all of the infrastructure disruptions that may have resulted. California is an area that has undergone several earthquake impact studies given its conspicuous seismic location. The 6.8 Richter magnitude Northridge Earthquake, that occurred in January of 1994, damaged infrastructure, particularly highways, in northern Los Angeles. Many impact methodologies have been used to study the economic implications of this event. The first economic impact methodology that will be analyzed in the case study is performed by Boarnet and published in the *Journal of Transportation and Statistics* [19]. The other is performed by and Gordon, Richardson and Davis also published in the *Journal of Transportation and Statistics* [13].

4.5.1 Analysis

The methodology to estimate the economic impact of the Northridge Earthquake used by Boarnet is a primary data analysis. An input-output model called the Southern California Planning Model (SCPM) is used in tandem with primary data analysis by Gordon, Richardson and Davis [13] in their Northridge Earthquake estimations.

Though these methodologies employ different tools, they examine the same spatial context. Boarnet's primary data analysis study focused on firms near the Los Angeles area. Boarnet also gathered data and estimated impacts in nearby regions within the state for comparison purposes. The SCPM study performed by Gordon, Richardson and Davis identifies impacts in more regions within the state of California than Boarnet's study, but still does not expand past the state boundaries.

Surveys were taken nine months after the earthquake and gathered information about the period before the survey, so Boarnet's primary data analysis captured short and long term impacts. The study that used the SCPM also used surveys as an input to this model. The time frame of impacts was determined by the survey's respondents, with some saying they felt impacts for days after the event and others reporting that they felt the impacts of the disruption up to a year after the event. Therefore, this study also captures both short and long term impacts.

Both methodologies resulted in highly disaggregated results. Boarnet chose to limit the distributional impacts analyzed because some sectors might experience either economic gains or disproportionately large losses. Essentially, this methodology actively tried to limit sectors that were outliers. On the other hand, the SCPM model analysis reported 15 different economic sectors and did not exclude any.

These impact efforts have the same goal of estimating business impacts of the Northridge Earthquake. Boarnet's surveys generate high-order effects of the earthquake. However, by using a different methodology, the Gordon, Richardson and Davis study is able to quantify the direct, indirect and induced employment and output impacts of business interruption. This framework categorizes these results as both direct and high-order effects.

Extensive surveying is required by both methodologies and is both time- and cost-intensive. The primary data analysis performed by Boarnet used survey responses from 559 firms in the Los Angeles area to provide information on the extent and magnitude of the business losses that could be attributed to the transportation damage caused by the earthquake. The input-output portion of the Gordon, Richardson and Davis study required estimates of final demand losses in output and employment in the 11 impact zones directly affected by the Northridge earthquake and the primary data analysis contribution to this study required telephone surveys of 528 firms.

The methodology exclusively using primary data analysis yielded dollar losses and self-reported percentage of those dollar losses than could be attributed to transportation damage. The SCPM methodology reported multiple economic metrics including dollar losses of output and companion job losses.

Unlike other economic impact models discusses previously, the models used in these studies do not prioritize visualizations to accompany data outputs. Neither methodology creates figures or maps that are illustrative beyond typical tables and charts.

4.5.2 <u>Summary Table</u>

Table 8: Northridge Earthquake Case Study Summary

	Boarnet	**Gordon, Richardson and Davis**
Methodology	Primary data analysis	I-O and primary data analysis (SCPM)
Spatial Context	City, intra-state region	City, intra-state region
Temporal Context	Short and long term	Short and long term
Distributional Impacts	Highly disaggregated	Highly disaggregated
Direct and High-Order	High-order	Direct and high-order
Data and Replication	Difficult to obtain, hard to replicate (individual surveys)	Difficult to obtain, hard to replicate (individual surveys)
Economic Output	Dollar losses	Dollar losses of output and companion job losses
Visualization Potential	None	None

4.6 Conceptual Framework – Organizing Concept

The goal of analyzing these methodologies by creating case studies is to discuss the different approaches than can be taken when studying the economic impacts of very similar events. Figure 9 below illustrates the interstate highway case study using the conceptual framework introduced earlier. Major disruption characteristics are outlined to identify the disruptive event being discussed. The impact assessment method, also outlined, estimates the “Effects” portion of the framework.

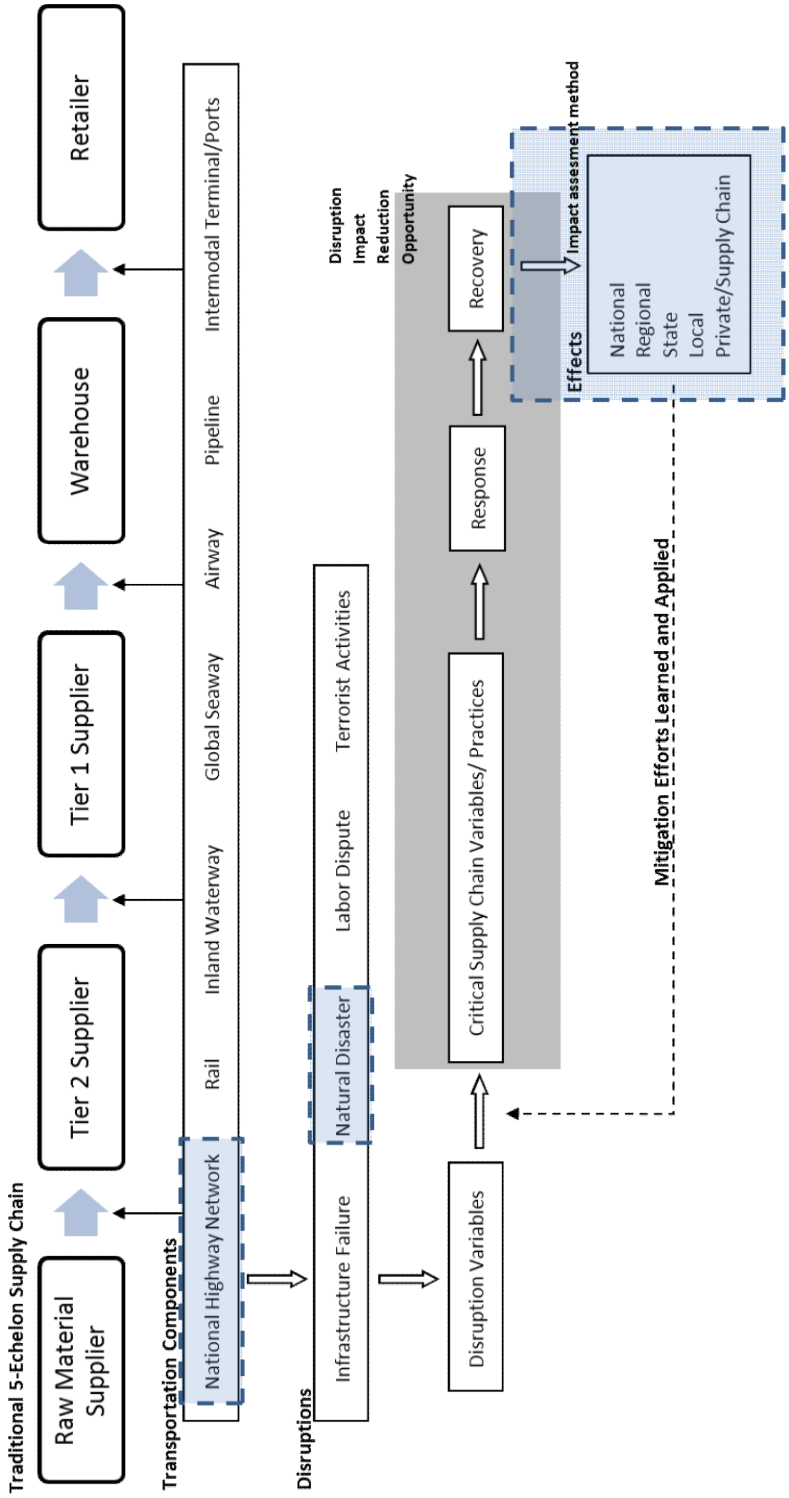

Figure 9: Conceptual Framework Interstate Highway Case Study

Figure 9 shows that these two events, the I-5 and I-90 disruptions in Washington State and the I-40 closing at the North Carolina - Tennessee border appear similar. However, they use very different methods to estimate their economic impact. What should not be overlooked is that, “I-5 is the principal north-south commerce corridor on the West Coast linking Canada to Mexico and connecting mega regions such as Seattle, Washington and Los Angeles, California” [20]. A disruption to I-5 likely catches freight in a different point of the supply chain than a disruption to I-40. Other disruption variables like time and availability of detours could also have a large impact. Therefore it may be more appropriate to conduct an impact study with a more extensive spatial context on this interstate than another interstate with less international significance.

CHAPTER 5

DISRUPTION IMPACTS – GOVERNMENT AGENCIES AND PRIVATE FIRMS

This chapter discusses how the private and public sector perceive, analyze and prevent freight disruptions. This will be accomplished by discussing how these different parties approach certain elements of this thesis' organizing framework. The specific elements that will be discussed are critical supply chain variables and practices, response, recovery and impact estimation methods.

The U.S. government and private firms using supply chains have a shared stake in the efficient performance of the transportation network used to move freight. When disruptions cause transportation networks to fail, both groups experience negative effects. To counteract and prevent these negative effects, certain measures can be taken. The measures taken by the government and private firms have the same goal of resilience, but are extremely different. Additionally, the perspective these two groups have when estimating negative effects is extremely different. Increasingly exposed supply chains coupled with increased frequency of disruptions makes a combination of government and private efforts all the more necessary to create a resilient freight transportation network [52]. Many effective efforts have already been taken in these fields. This chapter will introduce and discuss them to assist more widespread use.

5.1 Government Agencies - Impact Estimation and Mitigation

Unlike private firms that use impact estimation to derive impacts on the scale of one company's supply chain, government is interested in how disruptions affect local, state, regional and national economies. Direct effects of natural disasters are costly, but indirect effects can be even more expensive. An example of this is the 2001 Nisqually earthquake in Washington State. Indirect or high-order effects in the six month period after the earthquake included $77 million provided by the Small Business Administration. [17]. Once these high-order effects have been estimated, the actions taken are not where to source materials or what inventory system to use, but rather what infrastructure needs to be built to increase a network's resilience or how to establish regulations managing access during disruptive events.

5.1.1 Critical Supply Chain Variables and Practices

Government agencies are not responsible for a company's supply chain practices and principles. However, the government can make a better effort to recognize that supply chains are global and not restricted by county and state borders. Recognizing this, agencies can adjust strategies based on the implications of this global characteristic. This brings up the point of whether or not disruption resilience should be approached from a state, regional or national level. An MIT Center for Transportation and Logistics report offers the following reasons for why government disruption plans should be made on large, regional level in addition to a state level [17]:

1. Infrastructure and supply chains are not limited by state borders
2. Disruptive events like earthquake or hurricanes can be in multiple states or cause effects in multiple states
3. Multi-state regions may share infrastructure or weather issues making planning easier on a multi-state level

4. Private sector companies do not have the resources to comply with every state's resilience plan

This list does not attempt to prove that states and the federal government do not have roles in resilience. Rather, these suggestions only point out that effective disruption planning may have to incorporate difficult multi-jurisdictional planning on a regional level and embracing this will enable better disruption resilience.

5.1.2 Response and Recovery

Response and recovery are actions that are taken during and after a disruption in order to enact contingency plans, repair the transportation system back to a stable state and improve freight movement to lessen future disruption effects. Actions taken by the government depend on the agency and level of government involved. Table 9 is provided in a RAND Corporation report for the American Association of State and Highway Transportation Officials Standing Committee on Planning. This table shows a list of government entities at the state and Metropolitan Planning Organization (MPO) level and their potential responses to disruptions. Disruption response action items identified in this table include:

- **State Emergency Management Agencies** facilitating coordination during a disruption
- **State DOTs** reallocating unaffected resources during rebuilding
- **Traffic Management Operators** measuring system performance

Action items identified that are part of the recovery process include:

- **State DOTs** expediting the process of reconstructing damaged infrastructure

- **MPOs** planning redundant transportation systems and provide knowledge of community and business needs

Table 9: Actions Organizations May Take to Improve System Resilience [53]

Organization	Role	Role in improving resilience by phase	
		Disruption	Response and recovery
State Emergency Management Agencies	Coordinate emergency response at local and state levels	Mitigate effect of disruption	
	Develop and maintain Emergency Operations Plans and Hazard Mitigation Plans	Mitigate effect of disruption	Facilitate coordination to improve system performance during recovery
State DOTs	Ensure safe and efficient operations of all transportation modes	Ensure that key resources be made available during a disruption	Speed reconstruction of damaged infrastructure; reallocate existing system resources to meet demand during system reconstruction
Traffic Management Centers	Observe system operations	Detect system-wide effects of a disruption	Facilitate measurement of system performance during recovery
MPOs	Perform long-term system planning and allocate region's transportation funding		Plan systems with redundancy and structural flexibility
	Maintain a model of the transport system	Identify system behavior during a disruption, facilitating response	Assist in reallocating resources to reduce performance degradation during a disruption
	Coordinate planning with needs of freight transport	Ensure system operation sufficient to respond to the disruption, mitigating effects	Quickly reconstitute key system assets to meet community and business needs

These suggestions are actions that can be taken by the listed organizations while only using an organization's existing knowledge database and capabilities. Some states, such as Washington, have researched how to create freight resiliency plans that go beyond these suggestions [17]. The report's objective and findings fit firmly in the recovery category. The authors point out that most work focuses on how organizations respond during disruptions and the immediate aftermath while, "very little research has been conducted on how organizations or regions should plan to recover economically from these disasters, and few states have any meaningful recovery plans outlined for their freight systems." The proposed plan has eight steps, the most relevant being:

- Step 2. Identify and quantify the objective of an FSR Plan for this region.
- Step 3.Conduct a vulnerability assessment of the region's transportation network.
- Step 4. Create public/private collaboration mechanisms.
- Step 8. Test the plan with a large scale simulation.

This plan takes the previously discussed suggestions for organizations like state DOTs and MPOs and formalizes them into a process that can be replicated by every state. This process includes several steps that require data collection and assessment. For the suggested Freight State Resiliency Plan to work, economic impact models should continue to be used correctly and developed further.

5.1.3 Impact Estimation Methods

While actions taken at the state and MPO level can be very beneficial, some suggest that the federal government should take the lead on disruption response and recovery [52]. Specifically, the federal government should be more aggressive in building an economic simulation capacity at the local, state, regional and national level. This simulation capacity should continue to develop models that study both the direct and indirect impacts of disruptions. Methodologies that incorporate direct impact estimation like the Freight Performance Measures program should be developed further to create a seamless impact methodology that estimates both direct and indirect economic impacts.

5.2 Private Firms – Impact Estimation and Mitigation

While the government may be most interested in catastrophic disruptions, private firms must be more responsive to disruptive events that have more frequency and lesser impact. Examples of these types of events include a delay at a port as a result of increased security-related inspections or a delay at a border crossing [54]. Since these events happen more frequently, the types of resilience measures used by private firms tend to be strategic, frequent incremental adjustments.

5.2.1 Critical Supply Chain Variables and Practices

There are supply chain practices that, while useful for increasing profits and efficiency, tend to amplify the negative effects. Handfield, Blackhurst, Craighead and Elkins of the NC State University Supply Chain Resource Cooperative contacted industry executives to gather what they felt were potential impacts amplifiers [15]. Some of the practices listed are:

- The extent to which a firm relies on global sources of supply
- The complexity of the product or process
- Concentration or clustering of suppliers

- Number of transfer points

There are also many ways to lessen the negative impacts of a disruption. This includes having private firms buffer against disruptions [12]. The ways to do this include:

- Increasing inventory held at warehouses, manufacturing locations, and distribution centers
- Increase planned lead-times beyond actual lead-times
- Use two or more suppliers for a critical input into a product or service

While these strategies are sound, this report recognized that they violate principles of lean supply chains. Lean supply chains result in increased efficiency, but call for slimmed-down systems with little redundancy or slack. More innovative strategies may then need to be practiced so that supply chains can operate at optimal efficiency while maintaining an appropriate level of resiliency. Where the disruption occurs in the supply chain has been found to be a driver of the severity of negative effects. Disruptions between a tier 1 supplier, which converts subassemblies into final goods, and the warehouse or distributor, have been found to be the most costly [5]. So, if any buffer tactics are to be used, they could be most effective at this level.

Another strategy suggested by Tang in an article published in the *International Journal of Logistics* [9], that creates more robust supply chain is to have more flexible transportation choices. This means relying on multiple modes of transportation, multiple carriers and multiple routes. These actions can be taken proactively and have benefits whether or not a disruptive event occurs. If a supply chain uses more flexible transportation choices and a disruption doesn't occur, this strategy still improves a firm's capability to manage supply. If a disruptive event does occur, then a firm can change modes of transportation rapidly.

5.2.2 Response and Recovery

A potentially helpful response action suggested by the NC State University Supply Chain Research Cooperative is to develop “Disruption Discovery Visibility Systems” [15]. This type of system would increase the speed with which firms are notified of disruptions and allow for quicker response. Some characteristics of this visibility system are the use RFID technologies to track containers at critical points, in the supply chain and predictive analysis systems to identify potential problems.

A common believe is that risk avoidance should precede risk reduction [11]. Risk avoidance is accomplished by recovery strategies rather than response strategies. These are actions that take place after the conclusion of a disruption. A necessary part of the recovery process is taking the effort to learn from disruptive events, or simulations of disruptive events. One way this can be accomplished is by creating detailed disruption incident reports to identify the main causes of a disruption and its effects [15]. These reports are completed with the help of impact estimation methods.

Another, more ambitious program that could be added after recovering from a disruption is an early warning system. This type of system, which is suitable for all industries, would simultaneously identify leading risk indicators, and update and analyze this data to monitor supplier performance [3]. Better knowledge of when a supplier might encounter a disruption would allow firms to use a supplier they would otherwise avoid when considering the risk associated with supplier uncertainty [21].

5.2.3 Impact Estimation Methods

Supply chain redesign is one of a private firm's goals when studying disruption impacts. Supply chain redesign is the process of reconfiguring routes and making strategic adjustments with the knowledge gained from past disruptions [15]. Since firm's using supply chains are not interested in national or state level economic effects, they have to use impact estimation methods that deal with smaller scale estimates. The typical outputs of these models would be estimates of inventory levels, the amount goods in transit, and the number unfilled orders given a disruption.

5.3 Conceptual Framework – Organizing Concept

This chapter discussed how the private and public sector perceive, analyze and prevent freight disruptions. The framework categories discussed in this chapter are mostly disruption impact reduction opportunities. These opportunities, combined with the methodologies to study disruptions and potential disruptions, create an iterative process of improving the resilience and performance of both supply chains and the freight transportation system. This relationship is illustrated in Figure 10.

This chapter separated the discussion of government entities and private firms because their approaches to this process are very different. The differences were specified previously, but in general government organizations will be involved in creating a more robust transportation network and improving communication, while private firms will be attempting to optimize their supply chain.

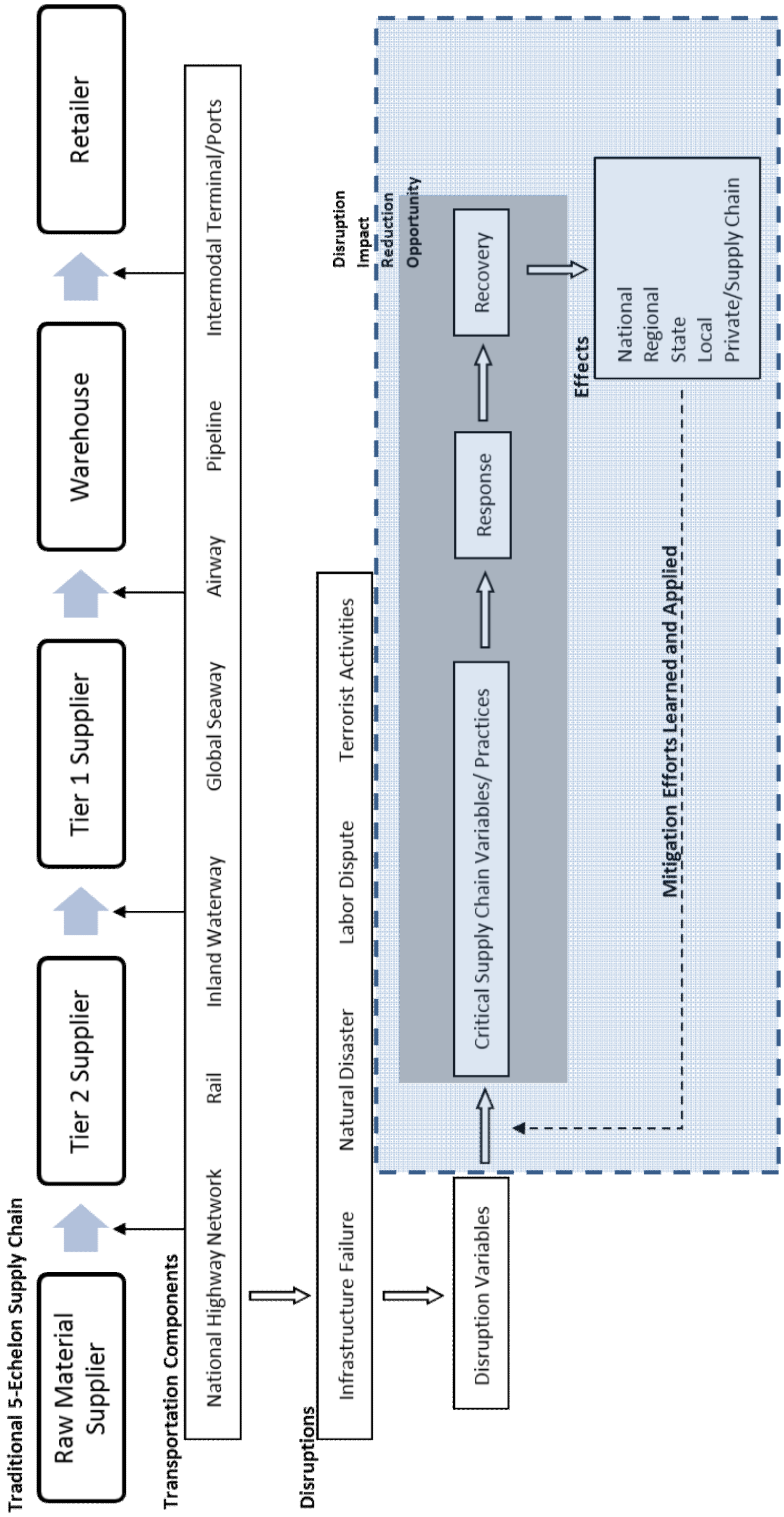

Figure 10: Conceptual Framework Impact Estimation and Mitigation

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This research has shown that many different approaches can be taken when studying the economic impacts of similar disruptive events, and has conceptualized the link between the supply chains, disruptions and their economic impacts. The movement of goods is a large percentage of the economy, and disruptions to this flow are extremely costly on every scale, yet there is no formalized process for studying these events and the effects they have on the economy. When a significant event occurs, such as a devastating hurricane or earthquake, there are usually multiple attempts to estimate its effect on the economy. Though these studies analyze the same event, several different methods are often used. This leads to, as it did in the case of the 2002 shutdown of the Los Angeles and Long Beach ports, a series of reports that either support or try to discount previous estimation efforts. This practice seems to be counter-productive and a misallocation of resources.

The global nature of supply chains is a trend that does not appear to be reversing. Many supply chain strategies that have yielded profit reduce inventory which can serve as a buffer against significant economic impacts. These leaner supply chains are not robust enough to withstand transportation disruptions, so the economic effects ripple through a local, state, regional and national economy faster than they would have previously. The following recommendations are aimed at identifying strategies that government entities and private firms can use to lessen the impacts of disruptions.

- **Create a formal process of economic estimation for various levels of government.** This process would be tailored to the government agency conducting the research and include a standard for the spatial and temporal extend of studies. The model does not need to be specified, but the outputs estimated do need to be specified. There are a number of methodologies for estimation purposes, yet studies often ignore the larger spatial consequences of events and in turn misrepresent the true economic impact.

- **Mandate, or incentivize a study to be conducted by MPOs identifying vulnerable infrastructure.** Mandating, or incentivizing this type of study with federal grants, would be the first step in formalizing infrastructure vulnerability as part of the project prioritization process. Including this as a part of the formula for transportation planning would inevitable make the freight network more robust.

- **Collect more detailed and accurate freight flow data.** An economic impact model is only valuable if the data used to generate figures is accurate. Almost every model studied required commodity flow information as a means to estimate economic impact. This should be a priority for the federal government if it intends to conduct more formalized research in the field.

- **Improve communication with private firms during disruption events.** Measures to prevent disruptions should be taken before measures to respond to them. However, it is impossible to prevent all disruptions from occurring. Alternative routes and disruption information should be passed along to freight dependent sectors by a dedicated service in order to effectively use unaffected resources that are not yet at capacity.

- **Give priority to freight flow while capacity is constrained.** This will not be a very popular policy, but it may be a necessary one. If the economic impact estimation process is required, and data is established that favor's this option, then negative impacts could be curtailed by allowing mostly freight flows through constrained transportation elements.

6.1 Future Research

There is no shortage of ideas for private firms to increase their supply chain efficiency. This thesis only listed the most common and relevant suggestions. Much of the research that was performed to make these conclusions was done on hypothetical situations. It would be interesting to see an estimation of how these tactics fared in the event of real disruptions. This would be a very difficult research effort considering the large number of variables involved, but a very worthwhile one.

There is certainly a large disparity in different states' progress in the field of disruption impact estimation and mitigation. A valuable research study would classify states in terms of their ability to estimate and mitigate disruptions and then see how these different classes fared economically while experiencing the same types of disruptions. If strong correlations were found between the progress in disruption mitigation efforts and subsequent economic impacts, there would be a much stronger case for more widespread policy adoption.

APPENDIX

GLOSSARY

Commodity Flow Survey (CFS) – data produced by an interagency effort on the movement of goods in the United States that provides information on commodities shipped, their value, weight, and mode of transportation, as well as the origin and destination of shipments of commodities [55]

Computable general equilibrium (CGE) analysis – able to model a broader range of higher-order impacts, typically referred to as "general equilibrium" effects, which, rather than being confined to economic interdependence (based solely on quantities of inputs and outputs), capture responses to price changes in factor and product markets [22]

Deterministic Simulation – loss estimation that involves the use of mathematical models, such as input–output or linear programming. Likely to be a must for estimating indirect effects

Direct economic resilience (DER) – the extent to which the estimated direct output reduction deviates from the likely maximum potential reduction given an external shock, such as the curtailment of some or all of a critical input

Direct impact – Property damage, on-site business interruption, or lives lost by disruption itself

Direct or technical requirements matrix – in an input-output model, **e**ach cell in a consuming industry column in the direct requirements matrix shows how many cents of the input from a producing industry is necessary to produce one dollar of the consuming industry's output and are called technical coefficients. Hence, the term "input-output"

Disruption – include natural disasters, labor disputes, terrorist activities, and infrastructure failures

Disruption Impact Estimating Tool – Transportation (DIETT) – an electronic analytical tool designed to assist transportation, security, and emergency-preparedness planners as they identify and prioritize potential high-value transportation choke points (TCPs) such as bridges, tunnels, and passes. Calculates the direct transportation and economic impacts (costs) of an event that precludes the use of a TCP

Distributional Effects Analysis – conducted to describe who is impacted by closures, where the impacts are, and what the intensities of the impacts are. The analysis helps generate additional spatial understanding of the economic impacts of the closures

Econometric model – include sets of simultaneous equations characterizing the entire economy and are capable of forecasting future economic growth and departures to it stemming from external shocks

Freight Performance Measures (FPM) Tools – program to assess the performance of freight movement on the U.S. transportation system. As part of this program, unplanned system disruptions are analyzed to assess impacts on measures such as average travel rate

Freight System Resiliency Plan – addresses the recovery of freight systems in order to preserve the economic viability of the state and region as a response to all hazards [17]

Hazard risks – weather disasters, equipment shutdown, or product liability [15]

IMPLAN – a 509 sector input-output model of the U.S. economy for 2001, available from the Minnesota IMPLAN Group, Inc.

Indirect impact – Input Output derived ripple or, multiplier impacts on a regional or national economy. For a more comprehensive dynamic economic analysis, would include macroeconomic and societal impacts. These include price effects, reductions in property values, impacts on import or export levels, and stock market effects, as well as aspects of sociological and environmental effects

Induced effects – "forward effects", economic ripples generated by employee spending

Input-Output model – integrated models of a national or regional economy used to estimate the total economic impacts, indirect transport-related economic losses

Interindustry transactions matrix – within an input-output model, the economy of an area is mapped out in table form, with each industry listed across the top as a consuming sector (or market) and down the side as a producing sector

Intervention analysis – provides a formal test for the change in the mean of a series as a result of an exogenous shock at a specific point in time [56]

Just-in-time inventory management – inventory reduction strategy requiring more frequent deliveries

Lead Time – product delivery time once an order has been placed

Long Term Effects – economic impact experienced more than one year after disruption

Long-Term Interindustry Forecasting Tool (LIFT) – an interindustry model with full "bottom-up" (commodity-by-commodity) accounting that can be used to examine the macroeconomic effects of industry-specific disruptions to imports [8]

Macro resilience – resilience at the macroeconomic level; extends as far as the indirect impacts of a terrorist attack or other disaster can go, which means the economy as a whole [57]

Macroeconomic impacts – the direct business interruption and direct business stimulus are injected into the broader economy subject to resource constraints to capture price and quantity interactions in multiple markets [18]

Markov decision model – determines an optimal inventory management policy and its resultant long-run average cost for a firm operating a supply chain subject to disruptions and uncertain lead times [58]

Meso resilience – resilience at the mesoeconomic level; includes the workings of individual markets and their interactions [57]

Micro resilience – resilience at the microeconomic level; includes both supply and demand (i.e., both the provision of a good or service and its utilization) [57]

Microeconomic impacts – individual behavior of firms, households, or organizations [18]

National Interstate Economic Model (NIEMO) – multi-regional input-output model of the 50 states and the District of Columbia (DC) which develops results for 47 economic sectors [29]

Primary data tabulation – data on hazard losses collected through internal assessment, questionnaire, interview, and telephone surveys [59]

Product complexity – the degree of difficulty in measuring and managing the number of different components and entities in the supply chain from supplier to end customer [15]

Recurring economic activities – economic activities that occur year after year and are a permanent part of the economy. The usual operations and maintenance of facilities are considered to be recurring (or on-going) economic activities [24]

Resiliency – the ability to cushion or mute potential losses from a natural hazard [22]

Short Term Effects – economic impact experienced less than 6 months after disruption

Spatial computable general equilibrium (SCGE) model – A computable general equilibrium approach is a loss estimation framework that considers spillover effects of catastrophes. When extended to a multiregional framework, the model is called a spatial CGE (SCGE) model [37]

Supply chain management (SCM) – the integration and management of supply chain organizations and activities through cooperative organizational relationships, effective business processes, and high levels of information sharing to create high-performing value systems that provide member organizations a sustainable competitive advantage [15]

Supply risk – delays which can be viewed as recurrent risks, or disruptions, which correspond to the interruption of supply [21]

System dynamics simulation – a perspective that considers the supply chain structure and the feedback inherent in these structures, has provided insights into supply chain behavior and has been used to investigate the effect of different policies on supply chain performance [5]

Total earnings/personal income effects – wages, salaries, and proprietors' income only. It does not include non-wage compensation (e.g. pensions, insurance, and health benefits); transfer payments (e.g. welfare or social security benefits); or unearned income (e.g. dividends, interest, or rent) [24]

Total local tax effects – revenues collected by sub-state governments. These are collected mainly from property taxes on new worker households and businesses, but also from income, sales, and other major local taxes in some areas [24]

Total State tax effects – revenues collected by state governments from personal and corporate income, state property, excise, sales, and other state taxes generated by changes in output or wages or by purchases by visitors to the region [24]

Total Federal tax effects – revenues collected by the federal government from corporate income, personal income, social security, and excise taxes

Transportation choke points (TCPs) – high value transportation elements such as bridges, tunnels, and passes located predominantly along major transportation routes [60]

Vendor Managed Inventory System – supply chain structure where customer demand is received differently. Both a supplier and retailer receive customer demand information [5]

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