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DEVELOPMENT AND ANALYSIS OF A GIS-BASED STATEWIDE FREIGHT DATA FLOW NETWORK

By

Anne Goodchild
Assistant Professor
University of Washington

Eric Jessup
Research Associate Professor
Washington State University

Edward McCormack
Research Assistant Professor
University of Washington

Derik Andreoli
PhD Candidate

Sunny Rose, Chilan Ta
MS Candidates

Kelly Pitera
PhD Student

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
1107NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation Technical Monitor
Barbara Ivanov, Freight Systems Division Co-Director

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16. ABSTRACT

In the face of many risks of disruptions to our transportation system, this research improves WSDOT's ability to manage the freight transportation system so that it minimizes the economic consequences of transportation disruptions.

This report summarizes 1) the results from a thorough review of resilience literature and resilience practices within enterprises and organizations, 2) the development of a GIS-based statewide freight transportation network model, 3) the collection of detailed data regarding two important industries in Washington state, the distribution of potatoes and diesel fuel, and 4) analysis of the response of these industries to specific disruptions to the state transportation network. The report also includes recommendations for improvements and additions to the GIS model that will further the state's goals of understanding the relationship between infrastructure availability and economic activity, as well as recommendations for improvements to the statewide freight transportation model so that it can capture additional system complexity.

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EXECUTIVE SUMMARY

Faced with a high probability that major disruptions to the transportation system will harm the state's economy, the Washington State Department of Transportation (WSDOT), in partnership with Transportation Northwest (TransNow) commissioned researchers at the University of Washington and Washington State University to undertake freight resiliency research to:

- Understand how disruptions of the state's freight corridors change the way trucking companies and various freight-dependent industries route goods,
- Plan to protect freight-dependent sectors that are at high risk from these disruptive events, and
- Prioritize future transportation investments based on the risk of economic loss to the state.

In order to accurately predict how companies will route shipments during a disruption, this research developed the first statewide multimodal freight model for Washington State. The model is a GIS-based portrayal of the state's freight highway, arterial, rail, waterway and intermodal network and can help the state prioritize strategies that protect industries most vulnerable to disruptions.

The report features two case studies showing the model's capabilities: the potato growing and processing industry was chosen as a representative agricultural sector, and diesel fuel distribution for its importance to all industry sectors. The case studies are found in sections 5.2 and 5.3 in the report and show how the statewide freight model can:

- Predict how shipments will be re-routed during disruptions, and
- Analyze the level of resiliency in various industry sectors in Washington State.

The two case studies document the fragility of the state's potato growing and processing sectors and its dependence on the I-90 corridor, while showing how the state's diesel delivery system is highly resilient and isn't linked to I-90.

As origin-destination data for other freight-dependent sectors is added to the model, WSDOT will be able to evaluate the impact of freight system disruptions on each of them. This will improve WSDOT's ability to develop optimal strategies for highway closures, and prioritize improvements to the system based on the relative impact of the disruption.

This research addressed several technical areas that would need to be resolved by any organization building a state freight model. First, the researchers had to decide on the level of spatial and temporal detail to include in the statewide GIS freight model. This decision has significant consequences for data resolution requirements and results. Including every road in Washington would have created a cumbersome model with a large number of links that weren't used. However, in order to analyze routing during a disruption all possible connections must exist between origin and destination points in the model. While the team initially included only the core freight network in the model, ultimately all road links were added to create complete network connectivity.

Second, as state- and corridor-level commodity flow data is practically non-existent, data collection for the two case studies was resource intensive. Supply chain data is held by various stakeholders and typically not listed on public websites, and it isn't organized by those stakeholders for use in a freight model. In most cases it's difficult to assure data quality. The team learned that the most difficult data to obtain is data on spatially or temporally variable attributes, such as truck location and volume. So they developed a method to estimate the importance of transportation links without commodity flow data. This method is discussed in detail in section 5.3.5.

Third, the freight model identified the shortest route, based on travel time, between any origin and destination (O/D) pair in the state, and the shortest travel-time re-route for each O/D pair after a disruption. The routing logic in the model is based on accepted algorithms used by Google Maps and MapQuest. Phase III of the state's freight resiliency research was funded by WSDOT and will result in improved truck freight routing logic for the model in 2011.

The two case studies showed how the state's supply chains use infrastructure differently, and that some supply chains have built flexibility into their operations and are resilient while others are not, which leads to very different economic consequences. The results of these case studies significantly contributed to WSDOT's understanding of goods movement and vulnerability to disruptions.

In the future, Washington State will need corridor-level commodity flow data to implement the research findings and complete the state freight model. In 2009, the National Cooperative Freight Research Program (NCFRP) funded development of new methodology to collect and analyze sub-national commodity flow information. This NCFRP project, funded at $500,000, will be completed in 2010 and provide a mechanism for states to accurately account for corridor-level commodity flows. If funds are available to implement the new methodology in Washington State, the state's freight model will use the information to map these existing origin destination commodity flows onto the freight network, evaluate the number of re-routed commercial vehicles, and their increased reroute distance from any disruption. This will allow WSDOT to develop prioritized plans for supply chain disruptions, and recommend improvements to the system based on the economic impact of the disruption.

1. INTRODUCTION

In the face of many risks of disruptions to our transportation system, including natural disasters, inclement weather, terrorist acts, work stoppages, and other potential transportation disruptions, it is imperative for freight transportation system partners to plan a transportation system that can recover quickly from disruption and to prevent long-term negative economic consequences to state and regional economies. In this report we

- provide a comprehensive review of the resilience literature,
- develop a geographic information system of the freight transportation network in the State of Washington,
- develop two industry case studies that consider the economic consequences of a disruption to the transportation network,
- specify the requirements of a statewide freight resiliency simulation.

The two case studies document lessons learned about the dynamics of those specific industries and the viability of the data collection process used in the study. They also demonstrate how differently two industries can use the transportation infrastructure.

A geographic information systems (GIS)-based, multi-modal, Washington state freight transportation network, when augmented with complete state-wide commodity flow data, will enable improvement in freight planning and infrastructure investment prioritization. Based on the case studies, we provide recommendations regarding the scope of and methodology for a statewide freight model that will be developed from the GIS network. This model can be used to estimate the vulnerability of different economic industry sectors to disruptions in the transportation system and the economic impacts of those disruptions within the State of Washington. The team interviewed public sector users to understand what applications are of value in a statewide freight model and applied the lessons learned through building the GIS and conducting the two case studies to make recommendations for future work.

1.1 BACKGROUND

Over the last ten years, the United States' transportation infrastructure has suffered from significant disruptions: for example, the terrorist events of September 11, 2001, the West Coast lockout of dock labor union members, and roadway failures following Hurricane Katrina. There is certainly an impression that these events are more common than in the past and that they come with an increasing economic impact. At the same time, supply chain and transportation management techniques have created lean supply chains, and lack of infrastructure development has created more reliance on individual pieces or segments of the transportation network, such as the ports of Los Angeles and Long Beach and Washington States' ports of Seattle and Tacoma. Disruptions, when they occur to essential pieces of the network, cause significant impacts. In particular, they cause significant damage to the economic system.

The relationship between infrastructure and economic activity, however, is not well understood. The research summarized in this report helps to increase the state's understanding of the sensitivity of economic productivity to infrastructure availability, laying the groundwork for reducing that sensitivity and improving the ***resilience*** of the transportation system, that is, improving the ability of the infrastructure to move people and goods in the face of transportation disruptions.

Resilience refers to a system's ability to accommodate variable and unexpected conditions without catastrophic failure, or "the capacity to absorb shocks gracefully" (Foster, 1993). Transportation resilience can be evaluated at various levels.

- At an individual level it means that people have transportation options needed to satisfy their transportation needs even under unusual and unexpected conditions, such as when their automobile breaks down, if they become physically disabled, or if their income decreases.
- At a community level it means that a transportation system can safely and efficiently accommodate unusual conditions, including construction projects, emergencies, and special events and gatherings.
- At a design level it means that facilities and the transportation system components can withstand extreme demands and unexpected conditions, including major equipment failures, disasters, and new technologies.

- At a strategic planning level it means that a transportation system can meet long-term economic, social, and environmental goals under a wide range of unpredictable future conditions.

An event is seen as disruptive when it creates unexpected conditions. If the future were predictable, resilience would lose its importance: individuals and communities would simply need to plan for a single set of conditions. But because the future is unpredictable, it is necessary to plan for a wide range of possible conditions, including some that may be unlikely but that could result in significant economic and social harm if they are not anticipated. Resilience is affected by a system's ability to collect and distribute critical information under extreme conditions. Resilience tends to increase if a system has effective ways to identify potential problems, communicate with affected people and organizations, and prioritize resource allocation.

This research was motivated by the desire of the Washington State Department of Transportation (WSDOT) to implement a Freight System Resiliency Plan (FSRP). This plan will allow the state to appropriately consider the requirements of the freight transportation system's users and the state economy when responding to disruptions to the transportation system. The WSDOT has completed Phase 1 of the WSDOT Freight System Resiliency Planning Process, which included the development and design of a conceptual approach to Freight System Resiliency Planning. The research, funded by the Freight Systems Division and carried out by the Center for Transportation and Logistics at MIT, included developing a thorough understanding of existing work in the area of freight system resiliency in order to develop a framework for analysis of the resiliency of the state transportation system.

Phase 1 was performed in four tasks: a review of the state of the practice, interviews with relevant stakeholders, development of the Freight System Resiliency Plan process, and knowledge transfer. Phase 1 resulted in 1) a methodology for creating, vetting, and implementing an FSRP for WSDOT, 2) a sponsored event at the Massachusetts Institute of Technology (MIT) bringing together private and public sector stakeholders to discuss the issues and exchange ideas, and 3) a synthesized review of the current state of the practice for other states' FSR plans. The most research-intensive step recommended by the research team was to develop

> a fairly detailed simulation analysis of the state transportation network. Each scenario will generate its own plan and analysis. The specific simulation model to conduct this analysis will vary from state to state (MIT Center for Transportation & Logistics, 2008).

This has become Phase 2 of WSDOT's freight resiliency research program and is summarized in this report. In addition to building an intermodal GIS network representation of the state's freight transportation infrastructure, we completed two case studies: a cross-Cascades disruption to the potato industry, and diesel distribution system. In the final section, this report recommends actions for improving the statewide freight transportation model including a comprehensive data collection program, a methodology for evaluating economic consequences, and integration into the statewide transportation planning process.

Phase 2 freight resiliency tasks include the following:

1) Provide a review of other organizations' assessments of the vulnerability of Washington's freight transportation system; this is summarized in Chapter 2.
2) Develop a geographic information system (GIS)-based portrayal of the transportation network that depicts, quantifies, and inventories the major freight flows in the State of Washington; this is documented in Chapter 4.
3) Create a map of freight flows by major industry sectors that use different aspects of the geographic transportation network; this was not possible because the data is not available.
4) Develop two specific case studies that consider the economic consequences of a disruption to the transportation network; these are summarized in Chapter 5.
5) Specify the requirements of a statewide freight resiliency simulation; this is summarized in Chapter 6.

1.2 NOTES OF CLARIFICATION

The following is an explanation of common terms and word usage within this report that might not be evidently clear to the reader.

- Within this report the term **network** (when used without any qualifier) refers to the freight transportation network within Washington state (or others). The term may refer solely to the roadway network, waterway network, rail network, pipeline network, or a combination of all four but is dependent on the context of the respective paragraph(s).
- The terms **supply network**, **supply system**, **distribution network** and **distribution system** refer to the elements that make up the collective transportation/distribution network in Washington state.
- Within this report an **incident** is an unplanned **disruption** to the **network**.
- Appendix A provides a list of acronyms used in this paper.

1.3 REPORT ORGANIZATION

This report summarizes the work completed through funding from the Washington State Department of Transportation on the topic of resilience. In addition, one paper has been accepted for publication and presentation at the 88th Annual Meeting of the Transportation Research Board, and two more have been submitted to the conference in August 2009. Through this work we have laid a foundation for the development of a methodology for estimating the economic significance of each component of the freight transportation system. The next section defines resilience in the context of the freight transportation system and provides a review of the related resilience literature. Chapter 3 describes current supply chain responses to disruptions. Chapter 4 describes the multi-model freight transportation network that has been developed for the state. Chapter 5 describes the potato and diesel case studies. Chapter 6 provides recommendations for data collection, future model development, and integration into the planning process. The report concludes with Chapter 7, and several appendices.

2. DEFINING RESILIENCE OF THE FREIGHT TRANSPORTATION SYSTEM

2.1. INTRODUCTION

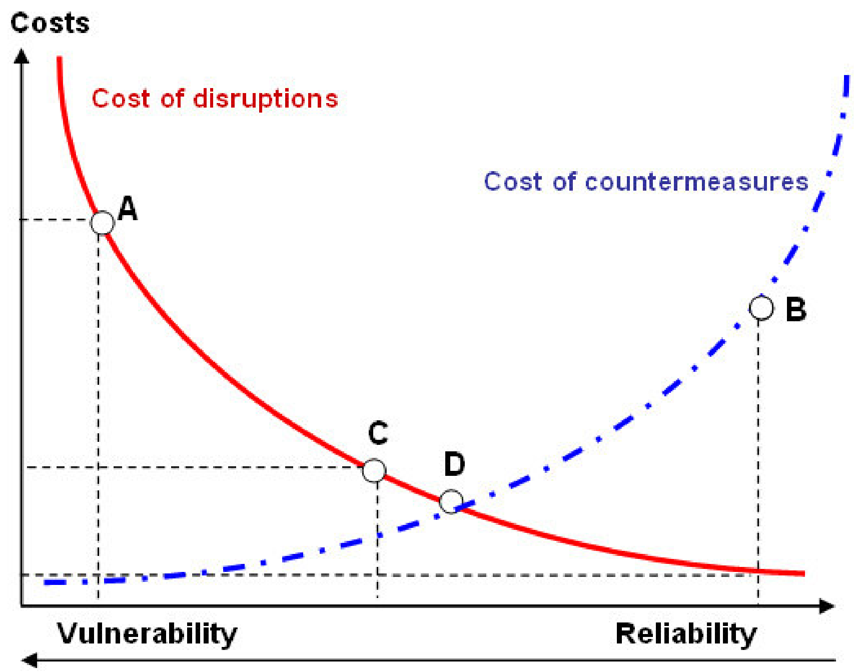
Resilience is a commonly used, although ill-defined, term in the context of freight transportation systems (FTS). By no means is resilience a new concept or a new theoretical perspective. However, not until recently has resilience emerged as an attribute of concern for businesses and their supply chains, transportation infrastructure, and, even more recently, by state departments of transportation (DOT) in relation to FTS management. In Washington state resilience has become a familiar part of the contemporary discussion of FTS, yet it lacks a widely accepted, standardized definition and agreed upon measures. Although some serious consideration of resilience in freight transportation planning has taken place at the statewide level, adequate quantitative tools for measuring resilience are lacking (MIT Center for Transportation & Logistics 2008). Definitions of resilience are somewhat clearer within the business supply chain context, but this is not true of FTS resilience in general (Godschalk 2003, Miles and Chang 2006). It is important to understand the resilience of the freight transportation system, which includes the physical and information infrastructure of the FTS, the system's managers, and the system's users. A consistent framework and definition for resilience can inform investment decisions, individual actions, and organizational behavior to build FTS resilience potential. Building a resilient FTS is critical, given the strong connections among freight, goods movements, and economic activity. In other words, the economic system is highly dependent on a reliable freight transportation system, and planners believe that a resilient FTS will be more reliable.

MIT recently completed a project for WSDOT outlining the process and benefits of freight system resiliency planning, jump-starting WSDOT's efforts to build a more resilient FTS. The MIT work translated the practice of resilience planning, typically called business continuity planning by private companies, to public agencies involved with freight transportation planning. In MIT's final report, "Development of a Statewide Freight System Resiliency Plan," the researchers defined resilience as "the restoration or recovery of the state's economy as it is affected, enabled, or disabled by the performance of the freight system" (MIT FRP 2008, 10), suggesting that resilience of the FTS is measured by "how quickly and efficiently [the FTS] can recover from a disruption" (MIT FRP 2008, 10). This definition of resilience highlights relationships between resilience, disruption, response, and recovery. Like the all-hazards mitigation planning conducted by state and local municipalities, freight resilience plans are motivated by the enormity of financial impacts to local and regional economies caused by disruptions resulting from disasters (MIT FRP 2008). Planning for FTS resilience has most directly influenced the response and recovery periods after a disaster, while assessment of vulnerabilities in the FTS has taken a secondary position.

A resilience perspective points to the responsibility that state DOTs have to consider their own role within the intricate web of relationships associated with goods movements, FTS infrastructure, and economic activity. The research from the MIT Center for Transportation & Logistics translated the benefits of resilience and business continuity planning, generally performed by private industry, to a public entity, a state DOT. The report extracted lessons learned from business continuity planning and applied the lessons to develop a process for freight resiliency planning (MIT FRP 2008). Most notably, the researchers focused on a "consequences" perspective. From a consequences perspective, disruptions to the FTS are classified by their impacts on the system rather than by the source of the disruption (MIT FRP). From the consequences perspective, resilience directs attention and resources on "tactic[s] used to reduce the occurrence of or mitigate the effects of disruptions" (Pitera 2009, 1). Resilience strategies, as defined by Pitera (2009), are employed by organizations, whether a managing organization or an FTS system user, to reduce response and recovery times. Although the vulnerability of the FTS is a related concept, there is greater focus on recovery than vulnerability. A focus on resilience and recovery allows for analysis of organizational characteristics and strategies that build resilience potential.

To date, assessing infrastructure vulnerabilities has been a primary method of measuring infrastructure performance in relation to resilience (Murray-Tuite and Mahmassani 2004, Rowshan et al. 2004, Hood et al. 2003). Assessment of the vulnerability of the FTS appears to be segmented across fields such as infrastructure engineering, supply chain management, and organizational performance (Cutter et al. 2003, United States 2003, Peck 2005, Fleming 1998).

As one example, Jenelius et al. (2006) and Berdica (2002) offered a demand side analysis of vulnerability, describing it as a user-oriented quality. In this study, vulnerability was juxtaposed with reliability to describe the non-operability and operability of the transportation network. Vulnerability was attributed to the infrastructure. The paired concepts of vulnerability and reliability were also examined by Husdal (2005) in a benefit-cost context that related vulnerability, reliability, and infrastructure investments (see Figure 2.1). Jenelius et al. (2006) further described vulnerability as the complement of reliability.[1]



Source: Hudsal 2005, 16.

Figure 2.1 The relationship between vulnerability and reliability costs

[1] Note: Vulnerability as it has been defined and applied in the transportation network context must be distinguished from the use of vulnerability within all-hazards mitigation planning and disaster research, which understands vulnerability as susceptibility of infrastructure or systems rather than non-operability. See Cutter, Susan L. 2001. *American hazardscapes: the regionalization of hazards and disasters*. Natural hazards and disasters. Washington, D.C.: Joseph Henry Press.

Beyond assessments of infrastructure vulnerabilities, efforts of state DOTs and metropolitan planning organizations to relate resilience to the FTS have included the following: enhancing their access to data, encouraging more detailed and comprehensive data collection, and increasing the accuracy of freight models.

2.2. DEFINING RESILIENCE

The ability of the transportation system to absorb the impacts from a disruption and continue moving traffic without deteriorated levels of service is one applied definition of resilience for FTS. This simple definition is the derivation of a dictionary definition, which defines resilience as "an ability to recover from or adjust easily to misfortune or change" (Rice and Caniato 2003). This initial definition of resilience hints at elements of flexibility and elasticity, the ability to continue operations after a disturbance. Although this interpretation is a good basis, further elaboration is important to understanding the FTS.

Resilience is a concept that permeates many fields. Insight gained from examining the literature on supply chains, enterprises, physical infrastructure, and emergency management and disaster research was applied across the three dimensions of the FTS:

1. the physical infrastructure
2. users (i.e., shippers and carriers)
3. the managing organization (i.e., state DOTs) (see Table 2.1).

The physical infrastructure consists of the network of nodes and links (e.g., port facilities, distribution centers, warehouses, intermodal yards, bridges, rail lines, and roadways) that support freight transportation, including the information infrastructure embedded in these facilities or located near them. Users include all organizations and individuals that use the infrastructure to transport people and goods. Users are typically private companies that are engaged in some degree of transportation of goods (e.g., agribusiness, retailers, wholesale sector, shipping lines, and trucking companies). The managing organization is the unit that oversees the construction, maintenance, and performance of the infrastructure. The actions and decisions of both users and managing organizations affect FTS resilience.

Table 2.1 Definitions: Resilience and dimensions of the freight transportation system

CONCEPT	DEFINITION
Resilience	The "ability to recover from or adjust easily to misfortune or change" (Bruneau et al. 2003).
Physical Infrastructure	The network of nodes and links (e.g. port facilities, distribution centers, warehouses, intermodal yards, bridges, rail lines, and roadways, etc.) and embedded ITS technologies and communication infrastructure that support goods movement.
System Users	Enterprises that move goods on the transportation infrastructure and use roadway information.
Managing Organization	The unit that oversees the construction, maintenance, and performance of the freight transportation physical infrastructure, and, more generally, the FTS. Activities include the management, utilization, and dissemination of roadway data (e.g., state DOT, public entity).

2.2.1 Supply Chains

Supply chain operators can take actions to improve the resilience of their supply chains. These are described in the literature as either "enablers" and "strategies" of resilience. Enablers "allow an enterprise to improve resilience" and include such concepts as flexibility and communication. Strategies "are specific actions that can have a measurable impact on an enterprise's ability to tolerate disruptions" and that are "used to reduce the occurrence or mitigate the effects of disruptions, allowing a supply chain to maintain or return to normal operating conditions" (Pitera 2009). Pitera provides a framework for assessing the resilience of enterprises' supply chains. This framework incorporates the supply chains' routine exposure to disruptions, perceptions of resilience and risk, and the actual supply chain resilience strategies employed by the enterprise (Pitera 2009). Her work on corporate resilience strategies provides insight into the resilience strategies of freight transportation system users and is of major importance to overall FTS resilience. For instance, the decision of a trucking company to cancel a route in its shipment plan equates to fewer trucks on the road and less demand for roadway capacity, which alters the state of the system and affects the impact of management decisions on the network's performance. Disseminating information regarding system performance, as a resilience strategy, will therefore improve system performance.

2.2.2 Enterprises

Resilience has also been studied in the context of the enterprise, where it is commonly, although not solely, attributed to the engagement of good communication within and between enterprises or private business organizations. In the example of private businesses, good communication helps develop corporate resilience potential. Good communication strategies must be diverse, flexible, and adaptable to support overall corporate resilience potential (Sheffi 2005). That is, the dissemination of timely and accurate information must use diverse avenues of communication that are also flexible and adaptable to change and uncertainty (Pitera 2009). However, good communication is but one resilience strategy for enterprises. Sheffi (2005) provided qualitative analyses of select companies that highlighted other strategies that include informal networks based on personal relationships, leadership at all levels, distributed power, and a results-driven corporate culture. These qualities of the enterprise support its ability to be flexible and absorb unanticipated disruptions in its supply chains (Sheffi 2005).

2.2.3 Infrastructure

In addition to enterprise resilience, resilience has been examined in relation to the physical infrastructure. In this regard, transportation resilience is defined as the timely ability of the infrastructure to absorb surges in traffic demand and recover from disruptions that compromise traffic movements. Fortifying infrastructure elements themselves contributes to faster recovery after a major natural or man-made disaster because the physical vulnerabilities have been addressed (USBTS 1998, Chang, Ericson, and Pearce 2003, Chang and Nojima 2001, Morlok and Chang 2004, Litman 2008). Methods for developing infrastructure resilience have also included operational strategies such as alternative routing, , the adaptive use of high occupancy vehicle lanes and the ability to transfer travel demand to non-single occupancy vehicle modes (USBTS 1998)..

Many studies have been conducted to understand the impacts of major disasters on transportation infrastructure, such as large earthquakes or terrorist attacks.[2] Tools

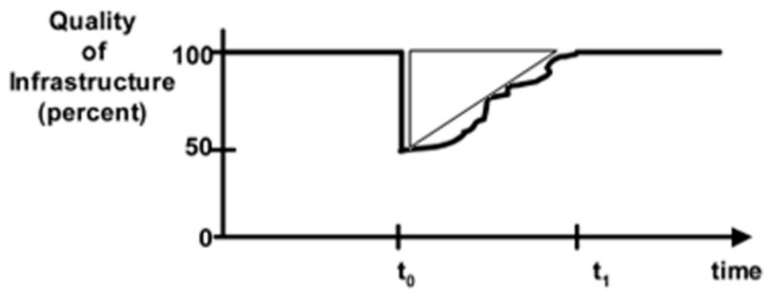
[2] For example, CREATE is a research center established in 2004 under the U.S. Department of Homeland Security. It is housed at the University of Southern California and performs work focused on risk and economic analysis.

have also been developed to assess the economic impacts of major disasters on transportation systems. REDARS2, developed by Werner et al. in collaboration with the Federal Highway Administration, uses network analysis to assess the seismic risk of "key lifeline routes" nationwide by addressing the seismic hazard related to each component of the highway system in terms of repair costs, down times, and time dependent traffic states (Werner et al. 2006). Cho et al. (2004) also modeled economic losses from transportation infrastructure damage by using the Southern California Plan Model 2 platform. Their model integrated seismic risk, the transportation network, spatial allocation, and I/O models to permit a study of the economic impacts of losses in production tied to transportation and industrial disruption in Los Angeles.

2.2.4 Disaster Research

A review of studies from emergency management and disaster research provides a greater breadth and depth of information on the resilience of network systems. Researchers with the Multidisciplinary Center for Earthquake Engineering Research (MCEER) define disaster resilience as "the ability of social units… to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters" (Tierney and Bruneau 2007). From a disaster research perspective, resilience concerns actions that contribute to social units' resilience before the disaster, during the disaster, and after the disaster to reduce the probabilities of failure, the consequences of failure, and the time of recovery. Disaster research generally falls into four categories of action: mitigation, preparedness, response, and recovery, each of which corresponds to a time period either pre-, during, or post-disruption (Haddow and Bullock 2004). Bruneau et al. (2003), frequently cited authors in seismic disaster and community resilience research, defined resilience similarly. They suggested quantification of a resilient system that incorporates "reduced failure probabilities, reduced consequences from failures, and reduced time to recovery," alluding to the importance of recognizing the differences between analyzing the resilience of a system prior to, during, and after a disruption (Bruneau et al. 2003). A specific resilience strategy may then be targeted to reduce the probabilities of failure, the consequences of failure, or the time for recovery.

The "resilience triangle" is a conceptual tool that "represents the loss of functionality from damage and disruption" (Tierney and Bruneau 2007). The resilience triangle communicates the magnitude of the impacts of a disruption. The depth of the triangle shows the severity of damage, and the length of the triangle shows the time to recovery. The resilience triangle does not, however, capture the probability of the disruption occurring. Figure 2.2 shows the resilience triangle for a 50 percent loss in infrastructure or system functionality. The smaller the triangle is, the more resilient the system, with lower severity of impacts and less time to recovery. The actions, behaviors, and properties of social units, organizations, and networks all contribute to reducing the size of the resilience triangle.



Source: Bruneau et al. (2003)

Figure 2.2 Resilience triangle

Considering pre-, during, and post-disruption time periods allows planners and decision makers to understand the impacts of specific resilience strategies on overall FTS resilience. Strategies can mitigate impacts and improve response and recovery. Many actions and behaviors that promote resilience are most applicable to pre-disruption actions or mitigation efforts. Mitigation describes actions and behaviors that are taken prior to any disruption that help curb the impacts of the disruption (Haddow and Bullock 2004). Examples of FTS mitigation efforts at the infrastructure dimension include seismic retrofitting of bridges and overpasses and investment in retaining walls, whereas at the organizational dimension, fortification strategies include prioritizing freight system users in anticipation of compromised infrastructure capacity and establishing processes that support efficient information sharing with freight users, allowing them to make appropriate decisions about how to best use limited infrastructure capacity. Despite the great benefits of planning for disasters and disruptions, few states have pursued formal freight resilience planning. Washington state is one of the few states to do.

Although not part of "mitigation efforts" as described above, the actions and behaviors taken by users and organizations during (response) and after the disruption (recovery) also affect FTS resilience. The rapid dissemination of information regarding the disruption and allocation of repair crews during the disruption immediately address reductions in capacity and give information to users who can then make decisions to optimize their use of the infrastructure (Brown et al. 2007, Oakland Tribune 2007). Mitigation efforts taken before a disruption contribute to increased resilience potential during and after a disruption, as well as prepare the system for the next disruption.

2.3. DEFINING RESILIENCE FOR THE FREIGHT TRANSPORTATION SYSTEM

The system's ability to absorb shocks and disruptions is related to the capacity for resilience in the physical infrastructure, the preparedness of the system's users, and the capacity of the managing organization to respond, engage resources, and make decisions (e.g., prioritize the use of limited infrastructure). The following discussion highlights all three dimensions.

Table 2.2 Definitions: FTS resilience

CONCEPT	DEFINITION
Infrastructure Resilience	the ability of the network to move goods in the face of infrastructure failure, either through a reduction in capacity, a complete failure, or a failure in the information infrastructure to provide information.
Enterprise Resilience	the ability of an enterprise to move goods in a timely and efficient manner in the face of infrastructure disruption.
Managing Organization Resilience	"the capacity to meet priorities and achieve goals in a timely and efficient manner in order to contain losses" (Haddow and Bullock 2004).
Freight Transportation System Resilience	the ability for the freight transportation system to absorb shocks and reduce the consequences of disruptions. Freight transportation system resilience can be deconstructed along its component dimensions: the infrastructure, the managing organization, and the system users.
Resilience Strategies	actions or behaviors of users or managing organizations, that promote resilience in one or a number of dimensions of the freight transportation system.

2.3.1 Freight Transportation Resilience at the Infrastructure Dimension

The physical infrastructure is the network on which goods travel. Resilience of the physical infrastructure is the ability of the network, given its capacity to supply lane miles and support throughput, to facilitate the movement of goods under capacity-constrained conditions. Furthermore, the infrastructure itself has the capacity to be resilient, given the design and quality of its materials and structures.

2.3.2 Freight Transportation Resilience at the User Dimension

Although FTS users are not solely responsible for overall FTS resilience potential, the actions of individual enterprises, no matter their size or function, do affect the system's performance, its ability to move goods, and the time it takes to return to a satisfactory level of performance after a disruption. For example, commercial vehicles must secure open loads and observe height restrictions to prevent potential disruptions. Also, during congested periods, system performance can improve if vehicles are re-routed or re-scheduled.

Enterprises—FTS users—rely on the infrastructure to move their goods. As the main providers and managers of infrastructure, government agencies are responsible for maintaining the quality and integrity of the infrastructure. Therefore, interactions between enterprises and the system's managing organization are necessary for both to build resilience potential. The policies of governmental agencies and the status and quality of the physical infrastructure both affect enterprise resilience potential. For example, often, a government's response to a disruption may have a greater impact on the enterprise's operation than the disruption itself. With regard to both large-scale and daily disruptions, the policies of federal, state, and local governments affect an enterprise's ability to move goods. Examples include federal policies such as the Customs-Trade Partnership against Terrorism (C-TPAT) and the Container Security Initiative (CSI), as well as local policies such as hazard mitigation plans (Rice and Caniato 2003). Enterprises that are able to disseminate information quickly, delay decision making, postpone shipments, and operate flexible supply chains have been found to contribute to the resilience of the FTS (Sheffi 2005). Thus, FTS resilience is a product of dynamic interactions among organizational entities—enterprises and the managing organization—and the physical infrastructure. Users contribute to FTS resilience to the extent that they and system managers are well connected, with dependable and trustworthy channels of communication and established relationships prior to the onset of a disruption.

2.3.3 Freight Transportation Resilience at the Managing Organization Dimension

A resilient organization both possesses characteristics and employs strategies to develop organizational resilience. In addition to being providers of infrastructure, the managing organization's role has grown to encompass transportation system operations and management. Understanding the resilience of the infrastructure allows the managing organization to more effectively manage, allocate, and deploy resources when preparing for and responding to disruptions.

There is increasing pressure on transportation organizations to provide more reliable infrastructure and to continue providing services during major disasters and disruptions. With these changing expectations, the concept of resilience management has emerged (McManus et al. 2008). This has occurred within a larger context in which the focus has shifted from post-crisis response to pre-crisis planning. The phenomenon has been observed not only in the United States but also globally (for an example see Britton and Clark 2003). This focus on pre-crisis planning highlights resilience because if organizations are to be prepared, they must be resilient. McManus et al. (2008) offered one definition of organizational resilience:

> Resilience is a function of an organization's overall situation awareness, management of keystone vulnerabilities, and adaptive capacity in a complex, dynamic, and interconnected environment (McManus et al. 2008, 82).

According to Bruneau et al. (2003), another definition of organizational resilience focuses on potential: "the capacity to meet priorities and achieve goals in a timely manner to contain losses" (Bruneau et al. 2003). To support the resilience defined by McManus et al. and Bruneau et al., organizations must possess certain characteristics and engage in certain strategies that promote resilience.

2.3.3.1 Characteristics of Resilient Managing Organizations

Somers (2009) found within the disaster research literature "six factors that will positively affect organizational resilience potential:

1. Perception of environmental risks by department manager;
2. Extent to which management seeks information about environmental risks;
3. Structure of the organization;
4. Extent of the participation in community planning activities;
5. Level of compliance with continuity of operations planning; and
6. Existence of professional accreditation" (Somers 2009, 13).

Somers (2009) focused his attention on a subset of these six factors:

- Organizational structure
- Participation in community planning activities
- Department accreditation.

He selected these factors because they are measureable at the organizational level and are significantly influenced by managers. Public works agencies were the site of Somers' analysis.[3]

[3] See Somers (2009) for explanation of the methodology and statistical analyses used to examine the six resilience factors.

First, organizational structure was measured along a continuum of centralization-decentralization, much related to long-standing debates over standardization versus local autonomy, control versus empowerment, and efficiency versus responsiveness. Somers' (2009) organizational structure hypothesis drew from Weick and Suttclife (2001). Somers (2009) assumed that "high resilience organizations vacillate between strong centralization during normal operating status and decentralized decision-making in times of crises" (page 13). High resilience organizations have an adaptive structure. Organizational structure was also identified by Mallak (1998) as an area that often presents barriers to resilience, specifically because many organizations' structures were established at times when technology, information, and avenues of communication were less advanced and less varied than those of today (page 6).

Somers (2009) used findings from Drabek (1990), who demonstrated the importance of good interpersonal relationships for successful multi-agency coordination during crises, to formulate the hypothesis that organizations with greater involvement in community planning activities better respond to disasters. Somers found evidence that participation in community planning activities with emergency service agencies tends to increase an organization's resilience potential.

Department accreditation by the American Public Works Association was the final factor examined by Somers (2009). The connection between organizational resilience and department accreditation was based on the need for agencies to "demonstrate 'full or substantial compliance' with a list of established practices," practices that relate to "comprehensive multi-hazard emergency planning; use of private resources; training and exercising; emergency supplies and equipment lists; community lifeline facility restoration; emergency facilities location; [and] emergency personnel policies and procedures" (Somers 2009, 14). However, Somers found only a weak link between department accreditation and higher organizational resilience.

In addition to organizational structure, participation in community planning activities, and department accreditation, Somers also found the role of managers and how they perceive risk to support three hypotheses:

1. Their behavior motivates them to take protective action against risk,
2. When people take protective actions they deem to be effective, the perception of risk decreases, and

3. The perception of risk accurately reflects behavior.

Applying these three findings at an organizational level, perceptions of risk are greater before an organization engages in planning activities. As the planning process is completed successfully, the perception of risk declines.

Performing research to gather information to answer 'why' questions also influences risk perception. Somers (2009) found that managers who conduct research and find information from seven or more sources more effectively build resilience than managers who seek or find information from six or fewer sources. Somers' interviewees expressed that it was relatively easy to access documents and reports from five or six sources, but information from less obvious sources, beyond the standard five or six, proved to be the most valuable in informing managers about risk, hazards, mitigation, and resilience building. As Somers explained it, "information gathering will tell us how [, but] not why; it is simply replication and not building knowledge and information gathering creates a product versus a process" (Somers 2009. 19). That is, seeking information from less obvious sources introduces new information that supports analysis of the underlying, explanatory reasons, or the 'why's' of a phenomenon.

Characteristics of resilient organizations are guided by effective and strong leadership. Brockner and James (2008) highlighted the relationships between characteristics of leaders and characteristics of organizations that include

- Treating causes not only symptoms
- Seeking views of multiple and diverse stakeholders
- Emphasizing short- and long-term outcomes
- Establishing norms for divergent thinking.

Both the ability of leaders to perceive opportunity during crises and the character and values of the organization work in combination to support organizational resilience.

2.3.3.2 Resilience Strategies for Managing Organizations

Organizational resilience potential is "the capacity to meet priorities and achieve goals in a timely manner to contain losses" (Bruneau et al. 2003). In addition to specific characteristics described previously, an organization's resilience potential also depends on resilience strategies. The definition of organizational resilience strategies is borrowed from Pitera (2009), who defined them as the "specific actions that can have a measurable impact on an enterprise's ability to tolerate disruptions" and that are "used to reduce the occurrence or mitigate the effects of disruptions, … [and] maintain or return to normal operating conditions" (Pitera 2009).

2.3.3.2.1 Resilience Strategies: Organizational Leadership. Literature on organizational resilience strategies generally focuses on enterprises. However, whether private or public, enterprises and managing organizations can benefit from qualities such as strong leadership, effective channels of communication, and informed planning. For example, organizational adaptation and learning may be more likely to happen when leadership sees crisis as opportunity. Specific resilience strategies will be more or less feasible given the combination of the leader's characteristics, organizational characteristics, and properties of the crisis.

First, an organization is only as strong as its employees. At the management level, opportunistic leadership facilitates strong organizational adaptation and learning. Opportunistic leadership draws on the following:

- Bricolage: "creating solutions out of whatever is available be it a crisis situation or an everyday situation that employees face regularly" (Mallak 1998, 2).
- Coping: "efforts to change behavior and attitudes to match taxing internal or external demands… to reduce the negative effects of stress" (Mallak 1998, 2).
- Self-efficacy: the ability to focus on the positives, not on the failures (Mallak 1998, 2).

2.3.3.2.2 Resilience Strategies: Employee Training. Organizational resilience potential expands when not only the leadership is prepared, but when all individuals throughout the ranks of the organization are prepared. Mallak's (1998) work further clarified this. He identified seven "resilience principles" drawn from a review of resilience concepts from disciplines such as psychology, social psychology, and organizational management. The seven resilience principles are the ability to

1. Perceive experience constructively (psychology)
2. Perform positive adaptive behaviors (psychology)
3. Ensure adequate external resources (organizational management)
4. Expand decision-making boundaries (organizational management)
5. Practice bricolage (organizational management)

6. Develop tolerance for uncertainty (psychology)
7. Build virtual role systems (organizational management) (Mallak 1998, 5).

2.3.3.2.3 Resilience Strategies: Communication. Timely dissemination of accurate information about the system's status underlies not only the organization's ability to be responsive, flexible, and adaptable, but also contributes to the overall FTS's resilience. The relationship between intra-organizational communication and resilience has been well documented in resilience literature and organizational literature. Organizational resilience potential is found to exist within organizations that promote information sharing, support quality and timeliness of information, and are successful in external dissemination of information (Sheffi 2005). In other words, the speed with which a managing organization can disseminate information establishes its "capacity to meet priorities and achieve goals in a timely manner… to contain losses" (Bruneau et al. 2003). Although the focus here is on strategies within an organization that build resilience potential for the organization, strategies for effective communication between a managing organization and its clients or partners is another aspect of organizational communication that deserves mention.

2.3.3.2.4 Resilience Strategies: A Process for Improving Organizational Resilience. This section outlines one example process for improving organizational resilience using organizational leadership, employee training, and communication (McManus et al. 2008). This involves cultivating situation awareness, identifying and managing keystone vulnerabilities, and increasing adaptive capacity. Each piece of McManus et al.'s framework is summarized below.

<u>Cultivating Situation Awareness</u>

McManus et al. (2008) drew their concept of situation awareness from Endsley. Endsley (1995) described situation awareness as the awareness of the individuals within the system, that is, individuals see themselves as part of a wider network and themselves as a network. Endsley (2003) likened situation awareness to an engine, one that drives decision making and performance in complex, dynamic systems. McManus et al. (2008) focused more on the situation awareness at the organizational level, using Oomes' (2004) definition of organizational awareness: "…an understanding of the multiple parties that make up the organization and how they relate to each other." Elaborating, McManus et al. (2008) further suggested that situation awareness includes "an enhanced understanding of the trigger factors for crises, an increased awareness of the resources available both internally and externally, and a better understanding of minimum operating requirements" (page 83). In other words, situation awareness should include an awareness of the expectations, obligations, and limitations of an organization in relation to internal and external partners. McManus et al. (2008) defined situation awareness "as a measure of an organization's understanding and perception of its entire operating environment" (page 83).

Coates (2006) suggested that situation awareness can be enhanced through scenario exercises. Actively running through pseudocrisis situations offers significant value for the networked organization and networked individual. Such exercises highlight the interrelationships between individual employees, their roles, and the functioning of the organization.

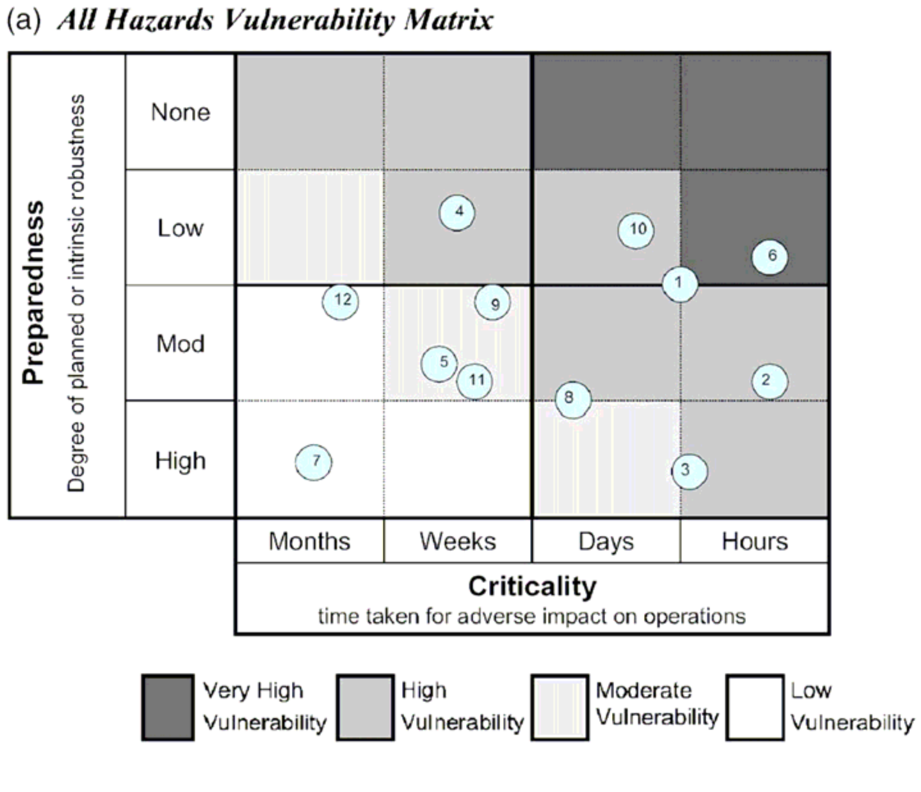
<u>Identifying and Managing Keystone Vulnerabilities</u>

"Keystone vulnerabilities are components in the organizational system, which by their loss or impairment, have the potential to cause exceptional effects throughout the system; associated components of the system depend on them for support" (McManus et al. 2008, 83). There are two types of keystone vulnerabilities, catastrophic and insidious. Catastrophic keystone vulnerabilities refer to an immediate failure of a system due to the sudden loss of a critical component. Insidious keystone vulnerabilities refer to "the failure of a system over time due to ongoing systematic or coincident loss of moderately critical components" (McManus et al. 2008, 83). As defined, keystone vulnerabilities include operational and managerial aspects of organizations that are both tangible and intangible.

Identifying keystone vulnerabilities involves determining two main criteria: (1) rapid or insidious, "the speed at which a component failure has a negative impact" and (2) discrete or cascading, "the number of component failures required to have a significant negative impact on an organization" (McManus 2008, 83).

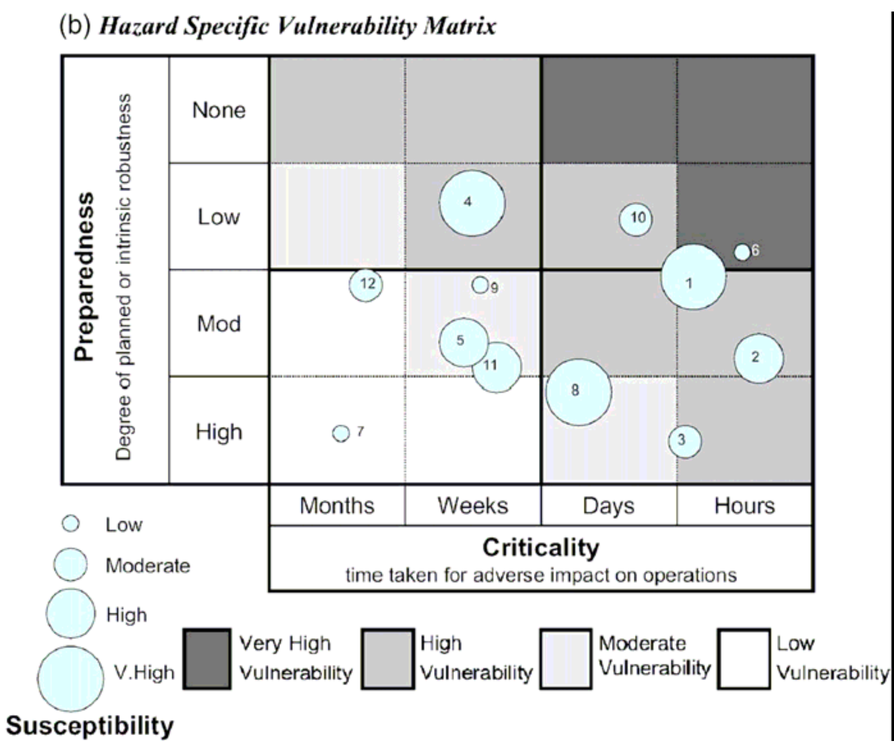
Identifying keystone vulnerabilities helps to cultivate situation awareness and promotes the development of adaptive capacity, for the identification of keystone vulnerabilities increases an organization's knowledge of its strengths, weaknesses, and capabilities. McManus et al. (2008) offered one method for cataloguing and categorizing vulnerabilities on the basis of criticality, preparedness, and susceptibility by using matrices based on an all-hazards approach and a hazard-specific approach. The matrices are reproduced in figures 2.3 and 2.4 for reference.

These vulnerability matrices are divided into four different zones represented by decreasing levels of preparedness (high, moderate, low, and none) that correspond to increasing levels of vulnerability (e.g., none, moderate, high, low). The matrices are also divided into four zones of criticality (months, weeks, days, and hours) that represent increasing frequency of occurrence. In Figure 2.4, susceptibility is represented by different sized "holes" to produce a context-specific matrix for each of the twelve generic hazards. In comparison, the all-hazards approach in Figure 2.3 attributes no weight to the twelve generic hazards.



Source: McManus 2008, 86.

Figure 2.3. Vulnerability matrix



Source: McManus 2008, 86.

Figure 2.4 Vulnerability matrix with susceptibility information

Increasing Adaptive Capacity

Adaptive capacity is at the core of current thinking on organizational resilience. "Adaptive capacity is a measure of the culture and dynamics of an organization that allow it to make decisions in a timely and appropriate manner, both in day-to-day business and also in crises. Adaptive capacity considers aspects of an organization that may include (but not be limited to) the leadership and retention of information and knowledge, as well as the degree of creativity and flexibility that the organization promotes or tolerates" (McManus 2008, 83). Drawing on McManus et al. (2008), "adaptive capacity is defined as the ability of an enterprise to alter its 'strategies, operations, management systems, governance structure, and decision-support capabilities' to withstand perturbations and disruptions" (McManus 2008, 83). Organizational characteristics that improve adaptive include positive behavior within the organization and within employees as well as the organization's and employees' ability to see disruptions and crises as opportunities rather than obstacles (Mallak 1998). Expanding decision-making boundaries, practicing bricolage, and building virtual role systems increase adaptive capacity. In a similar vein, treating causes not only symptoms, seeking views of multiple and diverse stakeholders, emphasizing short- and long-term outcomes, and establishing norms for divergent thinking are organizational characteristics that support a culture and dynamic associated with adaptive capacity and organizational resilience potential.

2.4. PROPERTIES OF RESILIENCE

A property of resilience is a sub-feature of resilience that can be narrowly defined and can encompass strategies that promote a system's resilience. Properties of resilience are applicable to dimensions independent of the other dimensions and independent of other properties. Properties of resilience may appear to suggest strategies that are in opposition if applied in isolation; however, with a systematic and holistic application property specific strategies will yield overall benefits to a system's resilience (MIT Center for Transportation & Logistics 2008).

Resilience properties can include apparent opposites such as redundancy and efficiency, diversity and interdependence, strength and flexibility, autonomy and collaboration, and planning and adaptability (Godschalk 2003, Miles and Chang 2006).

As already discussed, various actions and behaviors taken by users and organizations may increase resilience. Foster (Oakland Tribune 2007) offered a starting point for identifying the essential properties. He identified 31 properties of resilience for complex systems for which metrics may eventually be developed. The reviewed literature suggests that six of these resilience properties, shown in Table 2.3, may be applicable to the FTS: redundancy, autonomy of components, collaboration, efficiency, adaptability, and interdependence (Chang, Ericson and Pierce 2003, Chang and Nojima 2001, Morlok and Chang 2004, Litman 2008, Murray-Tuite 2006).

Table 2.3 Definitions: Six properties of FTS resilience

CONCEPT	DEFINITION
Redundancy	the availability of more than one resource to provide a system function.
Autonomous Components	parts of a system have the ability to operate independently.
Collaboration	the engagement of stakeholders and users in freight transportation system to promote interaction, share ideas, build trust, and establish routine communication.
Efficiency	the optimization of input against output.
Adaptability	system flexibility and a capacity for learning from past experiences.
Interdependence	the connectedness of components of a system or the dimensions of a system, including the network of relationships across components of a system, across dimensions of a system, and between components and dimensions.

These six properties of resilience in a transportation system are by no means comprehensive or exhaustive; however, these properties can contribute to the overall ability of the FTS to recover from disruptions, whether exhibited at the infrastructure, organizational, or user dimension (see Table 2.4). The contribution of each property to overall FTS resilience is summarized in the right-hand column of the table.

Table 2.4 Six properties of resilience applied to the FTS

PROPERTIES[a]	EXAMPLES OF APPLICATIONS OF RESILIENCE: PHYSICAL INFRA-STRUCTURE DIMENSION[b]	MANAGING ORGANIZATION DIMENSION[b]	USER DIMENSION[b]	CONTRIBUTION TO FREIGHT TRANSPORTATION SYSTEM RESILIENCE
REDUNDANCY[c]	Availability of multiple & alternate routing options	Multiple information sources & points of delivery	Multiple parts & materials suppliers; information backed up on distributed servers	Promotes flexibility; supports robustness
AUTONOMY OF COMPONENTS	The ability of highway system to function when air space closed; independent signal controls for each intersection	Independence of functional units in an organization, e.g. approvals & decision making can be independent of established hierarchies	Independence of functional units in an enterprise, e.g. procurement, billing, manufacturing, & distribution	Supports system operability despite the failure of individual system components; supports robustness
COLLABORATION	[not applicable at the infrastructure dimension]	Good internal communication across divisions & external communication with system users ; leadership across all levels of the organization	Public-private partnerships to build relationships between organizations[e]	Supports innovative problem solving, reduces mis-communications, spreads risk across groups
EFFICIENCY	Network designs that reduce travel time between origin and destination	Use of effective mechanisms to prioritize spending within the organization and on infrastructure	Coordination across the supply chain with relationships built across the different parties[e]	Allows resources to be spent on activities or projects that provide most benefit to the users
ADAPTABILITY[d]	Designed with short life-spans & the intent for regular replacement; ability to assume diversity functions (e.g. adaptable-use HOV lanes)	Familiarity of roles and responsibilities across levels of the organization; cross-trained employees ; leadership can be engaged at all levels	Ability to postpone decision making & shipping; build-to-order business model[e]	Promotes flexibility & system efficiency; supports robustness
INTER-DEPENDENCE	Seamless mode transfers ; intermodal facilities	Relationships are established across separate, but related agencies & within agencies ; mutual understanding of the value & benefit from interaction	Standardization of parts & interchangeability[e]	Exhibits smooth connections and transitions across parts of the system ; promotes system efficiency ; spreads risk across the system to reduce risk

[a]The seven properties adapted from (Tierney and Bruneau 2007).
[b]Examples of the property of resilience; not comprehensive or exhaustive.
[c]Further mentioned in (Haddow and Bullock 2004).
[d]Further mentioned in (Litman 2008).
[e](Sheffi 2005).

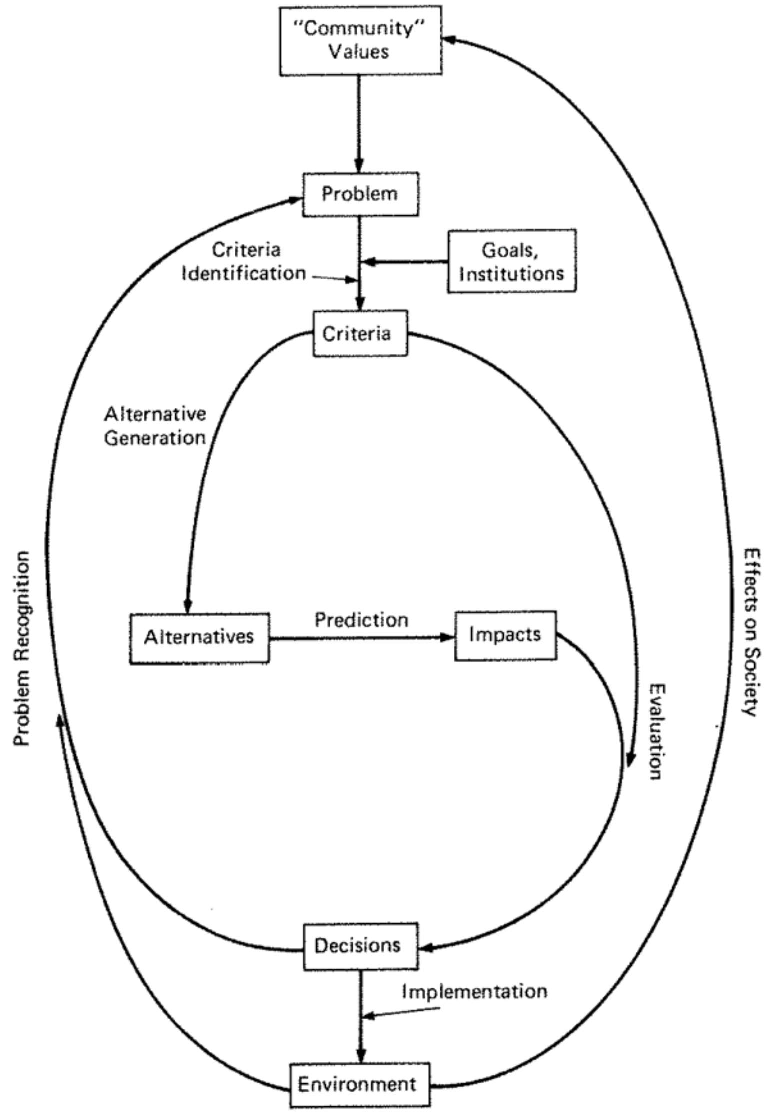
Note that the contribution to overall FTS resilience of each of the six separate properties is not mutually exclusive. Resilience strategies that promote adaptability may also promote efficiency. Moreover, not only are the contributions to resilience overlapping, but some properties may appear to be in conflict (e.g., autonomy of components and interdependence). Although individual properties of resilience may independently contradict one another, resilience of complex systems, like the FTS, is achieved through tradeoffs between strategies. The tradeoffs are a function of the type of system, the extent of the system under consideration, the particular nature of the risks involved, and properties of the disruption. Therefore, it is difficult to suggest a specific course of action, applicable under all disruption situations, that will fortify FTS resilience. Given the diverse applications of resilience to specific systems and situations, a case study method of analysis must be undertaken to identify the appropriate strategies that might be pursued along each dimension for a particular system. Note also that a single decision making body is not characteristic of the FTS, and there is not one party for whom resilience is the main and only priority.

2.5 FREIGHT MODELS, ANALYSIS, PLANNING, AND DECISION-MAKING

The overall ability of the managing organization of the FTS to better respond and recover from disruptions across each dimension of the FTS is facilitated by a clear understanding of resilience. Models are often used to represent operations, evaluate scenarios, identify weaknesses, project future change, and assess impacts from disruptions along the transportation network. Modeling provides information for strategic planning, identifies growth trends, identifies future problem areas, analyzes the effectiveness of potential solutions, and assists in setting project priorities.

2.5.1 Transportation Analysis Framework

General conceptual models documenting transportation analysis and planning processes abound. Drake (1973) offered one general framework for transportation analysis, reproduced in Figure 2.5. Drake's (1973) framework presents modeling and the modelers in a larger system of relationships that recognizes the importance of society, the greater environment in which decisions and planning take place, and the expectations of the community.



Source: Drake 1973, 43)

Figure 2.5. Transportation analysis framework

In Figure 2.5, the "problem" is the transportation issue or policy question under consideration. An understanding of the problem itself is bound by the environment in which modelers and decision-makers operate. Modeling is not directly represented in the diagram because modeling is just one of the many tools analysts can use in transportation analyses. Modeling has become perceived as a valuable tool for generating alternative solutions to a transportation problem and for predicting the impacts of those alternatives.

Much of the success in modeling depends largely on a thorough understanding of the processes being modeled and the larger system within which modeling is performed

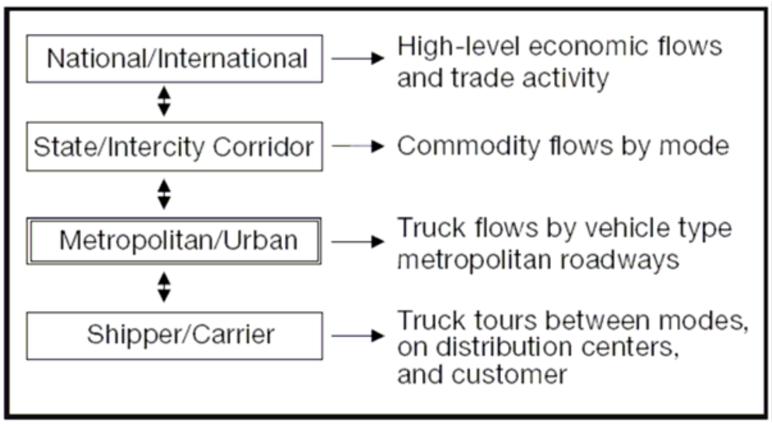
The processes involved in freight transportation modeling are complex. Given the size of and enormously conflicting interests related to major transportation projects, particularly those that involve the public, it makes sense that the consensus seeking and decision-making process is so complex. Decision-making is the product of multiple individuals and parties and occurs at various points along the project's evolution. With many moments for decision-making, the ability to model the impacts of decisions is a meaningful tool for assessing alternatives and providing information about the implications of decisions. Modeling is becoming more common in transportation analysis with the advancement in computing technologies, improved data gathering techniques, and economic evaluation.

2.5.2 Modeling and Freight Transportation Planning

Modeling freight movements proves to be more complex than modeling passenger vehicle movements. Much of the complexity stems from the number of different agents that influence shipment decisions, the vast array of commodity types, and the variation in entities that ship and receive these commodities. For instance, truck trips are not only influenced by the road network, time of day, and day of the week, but also by such factors as hours of service and operation, weight restrictions on roadways, truck types, the commodity carried, shipment size, and the availability of intermodal facilities.

Much in the way of freight modeling has been done at the metropolitan level. Kuzmyak (2008) provided a systematic and in-depth review of issues faced by agencies trying to model freight movements. Core metropolitan planning concerns relate to congestion, roadway safety, environmental impacts, noise pollution, and infrastructure damage (Kuzmyak 2008). However, greater confidence in modeling could be achieved with more information on the relationship between passenger and freight transportation interactions, data integration, data disaggregation methods, and economic impacts resulting from transportation disruptions. Furthermore, interagency partnerships are becoming more common as more states pursue statewide modeling.

Statewide freight modeling raises another set of unique questions. Kuzmyak (2008) offered a modeling hierarchy to organize levels of geography, levels of jurisdiction, and related modeling opportunities. The modeling hierarchy is reproduced in Figure 2.6.



Source: Kuzmyak 2008, page 11.

Figure 2.6 Freight modeling hierarchy

The "metropolitan/urban" level is highlighted because this is the level at which most freight modeling had been done. Metropolitan level modeling can rely on the output of state models to produce information on truck trips that occur on the boundaries of the metropolitan region. From a statewide perspective, it is worthwhile to consider the roles and uses of a statewide freight model that accounts for and builds off of existing freight modeling efforts. A few questions of relevance are as follows:

- What purpose does a statewide freight model serve if many metropolitan planning organizations are already pursuing regional modeling?
- What kind of model platform should be used?
- Who should house the model and how should it but used?
- How shall data be acquired and integrated?

Given the existence of metropolitan and regional level freight transportation models, an integrated model may be a logical platform for a statewide freight model, one that connects existing regional models to provide statewide flows. Further, it "should be easy to explain to an informed audience and easy to justify to an interested public" (Horowitz 1999, 117). Kuzmyak (2008) cited Turnquist's (2006) recommendations for model characteristics that are important for effective freight models: outputs are accessible and tailored to end users; important variables that represent interactions and how the system works are included in the model; the model is verifiable and understandable; and data that are used in the model are calibrated and tested (Turnquist 2006).

2.6 TYPES OF FREIGHT TRANSPORTATION MODELS

No model can perfectly predict the future. Models are by definition, simplifications of reality and as such do not include all the complexities of the real world. By design, models capture the important characteristics, but not all characteristics, of the modeled system. In doing so, they can be used to evaluate alternative scenarios in comparison to baseline scenarios.

Models provide valuable insight if their applications and limitations are known. Three general types of models related to freight transportation modeling are discussed below. Most studies of truck trips fall into two main types of truck trip models, the vehicle-based model and the commodity-based model. Vehicle-based models capture the movement of individual vehicles, while commodity-based models start from aggregate freight flows by weight (e.g., tonnage) that can be converted to units of truck trips. The respective ‘bottom-up’ and ‘top-down’ approaches of the vehicle-based and commodity-based models necessitate different data requirements. In addition to vehicle-based and commodity-based models, transportation network models are also presented in this report, followed by a discussion of integrated models. Figure 2.7 outlines the modeling hierarchy used to organize this discussion.

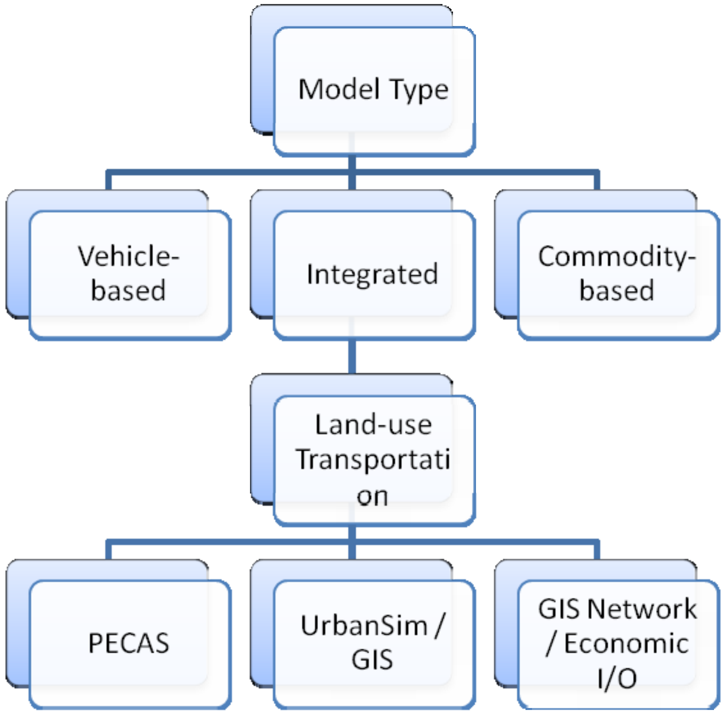


Figure 2.7. Freight modeling categorization

2.6.1 Vehicle-Based Models

A freight transportation model built on a vehicle-based platform models vehicle trips directly. The mode of travel and vehicle choice (usually in the unit of truck trips) are assumed to be limited to one mode. Empty trucks are not an issue with vehicle-based models because, for purposes of traffic impacts, one empty truck essentially plays the same role as a fully or partially loaded truck. Chow (2004) succinctly summarized such vehicle trip-based models, citing Jack Faucett Associates (1999):

> In Jack Faucett Associates, (1999) trip-based models are described as an approach in which truck trips are generated directly, usually as a function of different land uses and trip data from trip diaries or shipper surveys. The trip rates are calculated as a function of socio-economic data (trips per employee) or land use data (trip per acre) leading to generation of trips. The generated trips are then distributed using some form or other of spatial interaction models, most commonly a form of gravity model. The gravity model is typically calibrated using trip length frequency distributions obtained from trip diaries (page 14).

Data are typically collected with commercial vehicle surveys (CVS) that query vehicle owners and establishments that ship or receive goods (e.g., warehouses, distribution centers, stores), as well as with roadside surveys and vehicle classification counts. The survey data are one basis for deriving trip generation rates and the network distribution of vehicle-trips; however, low CVS response rates are a major challenge to the data integrity of vehicle-based models (Chow 2004, Fischer and Han 2001). Counts may also be used in conjunction with CVS to validate data. The high variability between data collection sites and the cost of securing large samples are also challenges to data integrity.

The high costs and labor requirements of administering surveys and the difficulty in achieving representative samples given the cost, time, and patience required by surveyors and respondents are all limitations of vehicle-based models. Certain actions can be taken to help improve the collection and analysis of vehicle-based data, such as focusing on land uses that are clearly freight intensive and performing research to better estimate the distribution of commodities within an industry. Fischer and Han (2001) and Jessup, Casavant and Lawson (2004) offered more in-depth summaries of truck trip data collection methods, the related challenges, and recommendations for improvements.

2.6.1.1 Simulation Models

Simulation models are one type of vehicle-based model. They are founded on a "learning-by-doing" principle. The learning mechanism of the model is calibrated by empirical data. Simulation models have sets of rules for vehicle behavior in each discrete time interval, and they step through time updating the states of vehicles according to these rules. They are capable of handling real-time data and can become extremely data intensive if they are to be accurate and useful. In comparison to the computational timeframes, on the magnitude of one or more years, on which many land-use models operate, simulations are able to process time increments on the magnitude of minutes. Simulation models have been used to inform the planning, design, and operations of transportation systems and can be performed at the micro-, meso-, and macro- levels (e.g., intersection, network of intersections, interstate systems). Typical sources of data for transportation simulations vary depending on the level of analysis. Examples include loop detector data, Global Positioning System (GPS) data, and vehicle classification counts. These are often readily available to modelers. Current implementations of simulation models are usually limited to intra-terminal operations or transportation corridors. The requirements for data inputs are heavy, as is the computing power required. For these reasons, simulation models have not yet been implemented at the state level.

2.6.2 Commodity-Based Models

Commodity-based models are another common methodology for modeling freight transportation. Commodity-based models use aggregated freight flow data, usually measured in a weight measurement such as tons, to estimate truck trips. The focus on freight flow data and commodity flow data highlights the connection between freight transportation and the economy. Chow (2004) suggested that commodity-based models "capture more accurately the fundamental economic mechanisms driving freight movements, which are largely determined by the cargoes' attributes (e.g., shape, unit weight)" (page 29). Commodity-based models have the following general structure:

1. Commodity generation models are used to estimate the total number of tons produced and attracted by each zone in the study area, the traffic analysis zone.
2. In the distribution phase, the tonnage moving between each origin-destination pair is estimated by using gravity models and other forms of spatial interaction models.
3. The mode split component, intended to estimate the number of tons moved by the various modes, is achieved by applying discrete choice models and/or panel data from focus groups of business representatives or freighters.
4. Prior to the traffic assignment phase of commodity-based models, a combination of vehicle loading models and complementary models that capture empty trips is applied to origin-destination matrices by mode to convert the tonnage into vehicle trips.
5. The vehicle trips are assigned to the network through a traditional assignment procedure.

With the aggregate nature of the data, commodity-based models fit regional-level analyses. The higher level of aggregation is usually above the scale of the standard traffic analysis zone used in the passenger transport model. The needed disaggregation is well summarized by Jack Faucett Associates (1999).[4]

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[4] See Chow (2004) for a paraphrase of the summary.

Commodity-based models typically rely on national Commodity Flow Survey (CFS) data collected by the U.S. Census Bureau of Transportation Statistics every five years. CFS data result from shipper surveys that detail commodity flows by quantities by mode on a state by state basis and, since 1997, by statistical metropolitan areas (SMAs). National CFS data are often disaggregated to the county level for use in statewide freight studies and models; however, the data are not always available to the metropolitan planning organizations (MPOs), the organizations that perform regional freight studies and modeling (Chow 2004, 32). In addition to the national CFS, Reebie Associates also provides disaggregated commodity flow data in its Transearch database for purchase. Given the aggregate nature of commodity flow data, to transform the data into truck trip generation rates, the flows are divided by payload data that have typically come from the national Vehicle Inventory and Use Survey (VIUS) (Fischer 2001, 2). Unfortunately, the VIUS is no longer conducted. A major drawback to commodity-based models is that they tend to underestimate urban truck movements because the aggregate flow data are unable to capture the details of many freight activities.

Despite the differences between freight transportation and passenger transportation, commodity-based and vehicle-based modeling efforts have taken the traditional four-step approach borrowed from passenger transportation modeling. The four steps are 1) trip generation, 2) trip distribution, 3) mode split and trip estimation (typically not applicable because the vehicle type is limited to trucks), and 4) traffic assignment. The process for this type of modeling is summarized in Table 2.5 alongside the process and for commodity-based models.

Table 2.5 A comparison of commodity-based and vehicle-based modeling approaches

Commodity based approach and platform		Vehicle based approach and platform	
Step	**Approach**	**Step**	**Approach**
Commodity generation	Commodity generation rates or zonal regression models, commodity flow data banks, Input/Output models	Trip generation	Trip generation rates or zonal regression models, seed matrices, traffic counts
Commodity distribution	Gravity models, logit models, Input/Output models	Trip distribution, logit models	Gravity models
Commodity mode split	Logit models based on panel data (usually n/a in urban areas)	Not applicable as single mode, trucks are directly estimated	
Vehicle trip estimation	Loading rates based on previous trip surveys	N/A	
Traffic assignment	Standard traffic assignment techniques	Traffic assignment	Standard traffic assignment techniques

Source: Chow 2004, 33.

2.6.3 Geographic Information System Transportation Network Models

Vehicle-based and commodity-based freight models require some representation of a transportation network by which to evaluate transportation decisions and alternatives. The GIS platform is one way to create a network representation. GIS is a well-developed field with standards for data representation and integration.

There is general agreement that a transportation network can be represented by nodes (e.g., ports, intermodal yards, distribution centers, and destinations) and the links (the system of roadways, rail links, waterways) that connect those nodes. A geographic information system (GIS) transportation network model is one representation of that system. The utility of a transportation network model is heavily dependent on the quality and form of data sources used. A GIS-based model "integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information" (ESRI website, accessed June 20, 2009). A GIS integrates databases with visual representations (i.e., maps) of spatial distribution, supporting analyses of events and scenarios structured on the modeled network. Impedance factors such as congestion costs, travel time, and truck route restrictions are built into the GIS network. Events and scenarios are modeled on the basis of the data available. In comparison to simulations, GIS network models do not inherently "learn," but they require modeler input to set up scenarios and run the model.

2.6.4 Integrated Models

Mentioned previously, freight transportation modeling at a statewide level should build off existing modeling efforts. There are three broad types of models that may integrate land-use, commodity flow, vehicle trips, and/or economic analysis: PECAS, UrbanSim, and a GIS network-I/O model. A statewide model involves more complex integrations to include not only land-use and transportation models, but also economic models and models designed for different scales of analysis. PECAS and UrbanSim are two commonly implemented systems for large-scale land-use and transportation modeling.

From the 1960s to the 1980s, transportation models focused mainly on roadway capacity and how to accommodate estimated demands generated by expected land-use development, represented by the spatial distribution of residential locations and employment centers (Waddell and Ulfarrson 2004). A recognition of the effects of transportation improvements on land-use development emerged during the 1990s. However, the complex feedback connections between land use and transportation need attention in the modeling world.

Integrated land-use transportation models comprise two distinct modeling pieces, the land-use piece and the transportation piece. In these models, the land-use piece generates the trips that feed the transportation piece of the model, which in turn generates the transportation demand on which land-use impacts can be modeled. Land-use transportation models usually draw on employment data, population density, and trip generation rates from standard sources such as the ITE Trip Generation Manual or surveys. Land-use transportation models are often used for long-term forecasting

2.6.4.1 PECAS

PECAS (Production, Exchange and Consumption Allocation System) provides a framework for representing transportation system elements, their behavior, and their interactions, and for identifying data needs to compare across different cases. The PECAS framework is not always used in its entirety; regardless, it is still used to define other model components as well as the interactions between those components. PECAS incorporates the spatial I/O approach of the MEPLAN[5] (Hunt and Simmonds 1993), TRANSUS (de la Barra 1998), and DELTA (Simmonds 1996) modeling systems. It is both an integrated and connected model. It is integrated because it is based on spatial disaggregation of I/O tables to link land use and transportation. PECAS is connected because it is able to model wide quantities of activities allocated in space according to distance of relevant accessibilities. Abraham and Hunt (1998) described PECAS as follows:

> an aggregate, equilibrium structure with separate flows of exchanges (including goods, services, labour and space) going from production to consumption based on variable technical coefficients and market clearing with exchange prices. Flows of exchanges from production to exchange zones and from exchange zones to consumption are allocated using nested logit models according to exchange prices and transport (dis)utilities. These flows are converted to transport demands that are loaded to networks in order to determine congested travel disutilities. Exchange prices determined for space inform the calculation of changes in space thereby simulating developer actions. The system is run for each year being simulated, with the travel disutilities and changes in space for one year influencing the flows of exchanges in the next year (Hunt and Abraham 2005, 217).

PECAS or its components is currently being applied in the development of state-wide transportation land-use modeling systems for Ohio and Oregon, in the development of an urban land-use model for Sacramento, and in the anticipated development of urban land-use models for Calgary and Edmonton in Canada. It is also being used as the basis for a recommended design for a model of the Los Angeles region.

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[5] MEPLAN was the modeling framework used for WSDOT's 2001 Cross Cascades Corridor Analysis Project. MEPLAN is a flexible, general framework that is based on many well established macroeconomic theories. "A review of the MEPLAN modeling framework from a perspective of urban economics" by John E. Abraham provides further details on a framework from which MEPLAN was designed.

2.6.4.2 UrbanSim

UrbanSim was developed to provide a tool for metropolitan planning organizations to "test out" policies beyond a long-term forecast timeframe. UrbanSim is a tool "to evaluate growth management policies such as urban growth boundaries, assess consistency of land use and transportation plans, and address conformity with respect to air quality implementation plans" (UrbanSim Description, http.//www.urbansim .org/description/, Accessed June 22, 2009). It is based on an urban model framework that accounts for agents, choices, and their interactions that relate to transportation, land use, and policy decisions.

The model implements a perspective of urban development that represents a dynamic process resulting from the interaction of decisions made by many actors within the urban markets regarding land, housing, non-residential space, and transportation. UrbanSim represents urban development as the interaction between market behavior and government action through land-use and transportation phenomena. Scenarios developed within UrbanSim are informed by population and employment estimates; regional economic forecasts; transportation system plans; land-use plans; land development policies such as density constraints, environmental constraints, and development impacts; all information to which most metropolitan planning organizations already have access. Outputs generated by UrbanSim support analysis down to the parcel-level; it is able to disaggregate information at the household, business, and land-use levels (UrbanSim Description, http://www.urbansim.org/description/, Accessed June 22, 2009).

UrbanSim has been used as a modeling in modeling efforts of cities such as Seattle, Washington, Salt Lake City, Utah, Honolulu, Hawaii, and Eugene-Springfield, Oregon (Waddell 2000).

2.6.4.3 Integrated Transportation Network and Economic Models

Researchers at the University of Southern California's Center for Risk and Economic Analysis of Terrorist Events (CREATE) have developed the Southern California Planning Model (SCPM). It is an integrated highway network-economic-spatial allocation model for the Los Angeles metropolitan area. It was designed to assess the economic impacts of terrorist threat scenarios affecting Southern California, of which transportation infrastructure and functioning are a major component (CREATE Accessed June 22, 2009).

REDARS2 is another integrated model. It includes modules for estimating seismic hazards, infrastructure component performance, and resultant system performance through the use of a transportation network model to represent the transportation system and assess economic consequences. The network model is simple and uses broad assumptions for estimating consequences, but it does not include commodity-specific costs or behaviors.

2.6.5 Modeling the Economic Impact of Freight System Disruptions

Estimating or measuring any economic impact resulting from transportation system disruptions may involve numerous approaches, depending on a variety of considerations. These include the attributes of the system being evaluated, data availability, static/dynamic time analysis, level of economic activity measured, accuracy of industry-to-industry relationship characterization, and utilization of output results. The different approaches are indicative of how intricate and challenging it is to accurately characterize and represent the complex and integrated way that firms/people interact in any economy (in this case the state's economy) and the challenges associated with developing a methodology that is simplified enough for practitioners/policy makers to understand yet robust enough to accurately reflect real economic and transportation activity.

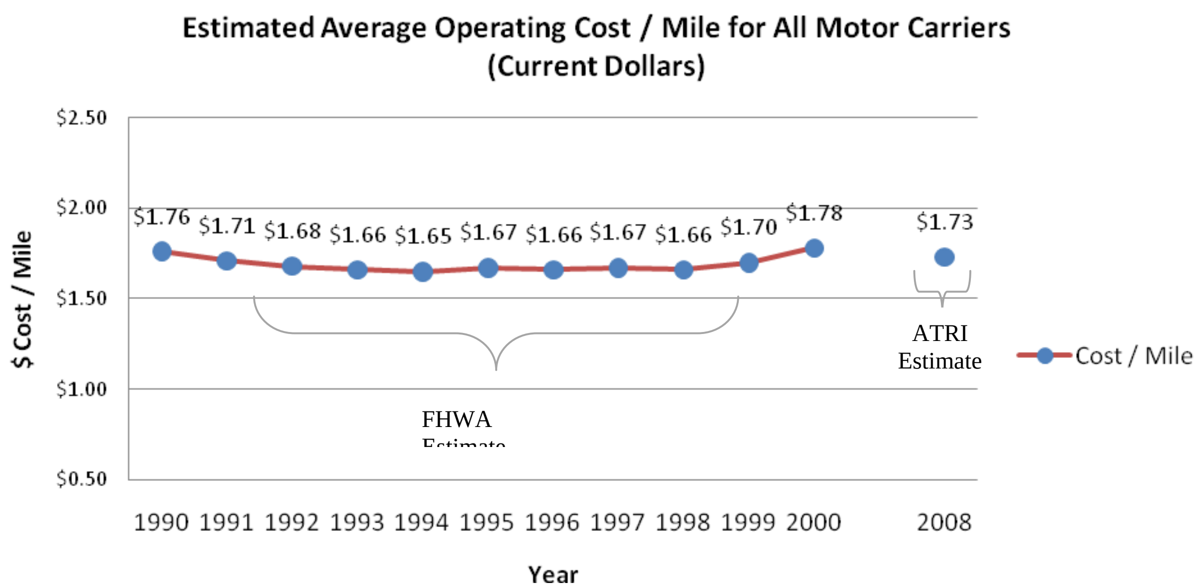
Economic impacts resulting from temporal disruptions to the transportation system can be classified into two categories: direct (short-run) and indirect (long-run) impacts. The direct economic impacts for highway system disruptions are principally concentrated in the freight transportation and trucking services industry, affecting variable operating costs to these businesses, but they can also have immediate implications to businesses and firms serviced by the freight industry, especially shippers of perishable and time-sensitive commodities (see Table 2.6). The impacts to businesses in the freight transportation and trucking industry include increased variable costs such as fuel, labor, scheduling/logistics, tire wear, and equipment maintenance that result from shipments being re-routed, delayed, or in some cases trans-loaded to another truck/trailer.

Table 2.6 Freight services/truck transportation cost components

Fixed Costs	
Fixed Business Costs	• Management/Overhead Cost • Insurance • Taxes • Interest
Fixed Vehicle Costs	• Truck and Trailer Equipment Depreciation • Truck and Trailer Licensing
Variable Costs	
Truck/Trailer/Vehicle Use	• Driver/Labor Cost • Scheduling/Logistic/Dispatch Labor Cost • Fuel Cost • Repairs/Maintenance • Tires • Miscellaneous

Depending on the location and duration of the disruption, trucking firms may incur additional lodging costs for truck drivers or be required to arrange/pay to switch drivers who have exceeded their hours of service limits waiting for the disruption to be resolved.

The Federal Highway Administration provided estimates of average operating costs per mile for all motor carriers up until the year 2000 (see Figure 2.8), which ranged between \$1.65 and \$1.78 per mile. A more recent 2008 study by the American Transportation Research Institute estimated the average operating cost for all motor carriers to be \$1.73 per mile. Utilizing these national average cost estimates and applying them to specific disruption scenarios provides an estimated range of direct cost impacts to freight transportation and trucking businesses. To apply these average per mile cost coefficients in aggregate, pervious simulation/modeling impact analysis is required to estimate the total volume of freight vehicles affected, likely re-routing scenarios, and the additional mileage incurred by transportation/trucking firms. If more concentrated direct cost impacts are desired at the industry or commodity level, then freight modeling/simulation analysis will need to be more detailed to provide specific freight volumes and re-routing activity at this level, as well as the additional mileage cost coefficients segmented by industry or commodity type.



Source: Federal Highway Administration (FHWA), Freight Management and Operations, http://ops.fhwa.dot.gov/freight/freight_analysis/exp_mile/index.htm
Source: American Transportation Research Institute (ATRI) http://www.atri-online.org/research/results/economicanalysis/Operational_Costs_OnePager.pdf

Figure 2.8. Estimated average operating cost/mile for all motor carriers

While this estimation approach provides a relatively quick and approximate estimate of direct impacts to trucking companies and freight shipping services in aggregate, it does not explicitly account for the special instances of additional lodging costs and driver replacement costs mentioned above. However, one could argue that because transportation disruptions, to varying degrees, occur periodically across the national transportation system, and freight shipping and trucking companies are continually responding and adjusting to these disruptions, a small portion of this cost component is already included in the estimated average cost per mile of operations. The direct costs of product shipments that are damaged/spoiled as a result of the transportation disruption and covered under the freight services insurance policy would result in higher insurance premiums for freight services companies that would further increase operational costs.

2.6.6 Indirect Economic Impact

The more difficult challenge of estimating the economic impacts from transportation system disruptions relates to how the disruptions affect the businesses and firms throughout the broader economy that rely upon freight transportation and trucking services. To fully understand how these impacts affect different types of businesses and firms requires a thorough understanding of firm-level decisions and activities, including all supply (production) and demand (consumption) relationships for a specific product. In Washington state, the number and variety of products/services produced is vast, including everything from airplanes, computer software, and agriculture products to outdoor recreation equipment. Likewise, developing a microeconomic model that accurately characterizes all supply and demand relationships for any one of these products would present a formidable challenge on its own and would be extremely difficult for all products and services combined in the broader economy in aggregate. As a result, many micro economists spend their entire careers focused on one specific industry or subset of products (environmental economists, energy economists, agricultural economists, etc).

Perhaps the most common approach to estimating and accounting for inter-industry activity is Input-Output Analysis, an approach first developed by Wassily Leontief, who won a Nobel Prize in Economics in 1973 for developing this type of economic accounting structure. Leontief was primarily interested in how technological change in certain businesses and industries affects the broader economy through multiplicative transactions and activities across all industries, firms and economic sectors. But his approach of identifying the specific input-output relationships for all major industry sectors was quickly adapted to many other economic policy issues, including how taxes and/or subsidies to any one specific industry affect all other industries as the tax/subsidy is traced throughout the entire economy and how the aggregate economy is changed. This approach has also been widely applied to estimating the economic impacts resulting from a large project (or series of projects/investments) in an economy when information about how those investments affect different industries is desired. This approach has also been applied in the State of Washington to estimate the economic impacts from two transportation system disruptions (I-5 flooding and I-90 Snoqualmie closure) (Ivanov et al. 2009) and to provide a better understanding of the significance of transportation services to the state's economy (Chase, Jessup and Casavant 2003).

Input-output accounting and modeling was initially quite aggregated, both in terms of industry classification and geographic specification, and this has been one of the principle criticisms of this type of modeling. Leontief initially developed an input-output accounting for the entire U.S., including only 40 industry sectors. The current and most widely used input-output package, IMPLAN Professional Software 2, includes nearly 500 industry sectors and allows geographic aggregation at the state, county, sub-county, and zip code levels (assuming one has purchased the sector activity data for the region of interest). The IMPLAN data consist of 1) a matrix of industry-specific technical coefficients that specifies the quantity of inputs necessary to produce a given unit of output and 2) sector-specific final demand, final payments, industry output, and industry employment.

While input-output models have been widely used and applied in many different circumstances, they do possess several limitations that are worthy of consideration. The technical coefficients (unless modified and modeled separately) are treated as constants, thus not allowing for businesses or firms to alter the number of specific inputs per product (output) produced across all inputs and outputs. Of course the actual economy and businesses participating in the economy do not work in this manner. In reality, firms are constantly adjusting and substituting inputs as market conditions, technologies, labor productivity, prices for labor and equipment, and the structure of the industry change. This limitation is especially problematic if this type of modeling approach is applied to longer-term implications or forecasting well into the future. This is one reason why these models are primarily utilized for one-time shocks to the economic system. In addition, input-output models assume zero resource constraints (supply is perfectly elastic) and that employment is efficiently allocated and operating at full capacity (zero underemployment). Neither of these assumptions is accurate, and this partial equilibrium solution poses problems or limitations when lengthy time periods are evaluated. Also, given that few regional economies (regardless of the region of interest, whether a collection of states, one state, or a county) function as a geographically isolated island, the identification and characterization of how the economy of interest engages and interacts with the broader economy is often difficult and therefore oversimplified. Lastly, the accounts and transactions level input data utilized for this approach are typically not made available without a two- to five-year lag. During periods of significant and sizeable economic change (as witnessed over the past two years), the industry-level inter-relationships from several years ago may not be applicable to current conditions and thus limit the accuracy of this type of approach.

Given the limitations with input-output modeling and the partial equilibrium outcomes provided (no price responses, constant input-output technical coefficients, perfectly elastic supply), a Computable General Equilibrium (CGE) model approach (part of the General Equilibrium family of models) is increasingly preferred and implemented. This family of models utilizes the same transactions level input data/information as a traditional input-output model, but it also approaches a "general" equilibrium solution by allowing all prices to change and the utilization of technical coefficients to adjust as a result of these input/output price changes. This approach certainly lends itself to economic analyses that cover longer time periods, since firms, markets and industries do adjust in the long-run. Of course the challenges (both information/data and mathematical) with this type of modeling involve precisely how these price responses are characterized and allowed to occur. More specific and applicable to transportation, and especially freight transportation, modeling, Spatial Computable General Equilibrium (SCGE) models have emerged and become more widely utilized. To accurately characterize the degree of dynamic inter-relationship across all products, commodities, and labor markets and industries is formidable to say the least, but it is especially challenging when we allow information on how businesses (both production and consumption activities) are geographically and spatially organized to be explicitly included and to influence demand/supply activities.

SCGE models have evolved and progressed substantially in the last ten years (Bröcker 1998, Bröcker et al. 2001) and have been applied in many different transportation modeling, and more recently freight network modeling, scenarios (Lakshmanan and Anderson 2002). This approach has been more developed and applied outside of the U.S., most notably in the development of the RAEM 3.0 Model[6] in the

[6] For a full description see Hhttp://www.tmleuven.be/project/raem/RAEMFinalreport.pdfH

Netherlands by Ivanova et al. (2002, 2007) and in Tokyo, Japan (Sato and Hino 2005). But considerable challenges still exist to integrate these SCGE models with purely freight network models and to address geographic aggregation issues, freight flow calibration/validation, and static vs. dynamic time horizons. Much of the earlier work has evolved from passenger travel models that have been adapted to represent freight activity. Unfortunately, freight transportation activities are substantially more complicated than passenger travel activities, are influenced by a greater array of variables, and are therefore much more difficult to accurately characterize in a modeling context.

3. CURRENT SUPPLY CHAIN RESPONSES TO SUPPLY CHAIN DISRUPTIONS

As global trade volumes continue to increase and supply chains lengthen, enterprises in all sectors of the economy are facing increased likelihoods of supply chain disruptions. Vulnerabilities exist in every segment of the supply chain, including the transportation network. Events within the United States, such as September 11th, the West Coast port labor lockout, and hurricanes Katrina and Rita, have highlighted the potential for transportation disruption within supply chains and the economic consequences of being unprepared. With the increased focus on disruptions and the continued desire to reduce cost, resiliency has become an issue of concern within the supply chain community. Supply chain disruptions can be divided into four main categories: natural disasters, accidents, intentional attacks, and those caused by government policies and regulations.

The research work documented in this section was not sponsored by the WSDOT but was carried out by a graduate student supported by scholarship funds. Her work, however, is important to understanding the infrastructure user, or enterprise, view of resilience and so is included here.

3.1 IMPORTANCE OF RESILIENCY

Resiliency within supply chains is not a new concept for importing enterprises, but recent trends in trade and supply chain operations have made resiliency more important, especially in light of transportation disruptions. Supply chains are becoming more complex as they are lengthened and leaned, and most supply chains are a dynamic network that is ever-changing (Christopher and Peck 2004).

The introduction of global supply chains means longer transport distances, additional modes of transportation, and more participants, which leads to more opportunities for disruptions (Sheffi 2005). Additionally, new languages, currency, and cultural traditions add complexity to supply chain operations, and customs and security regulations must be met to move goods into or out of the country. These factors associated with lengthening the supply chain lead to an increased potential for disruptions to the goods movement system.

Lean operations, instituted as a means of reducing logistics cost, leave little slack in the system to handle unforeseen problems. In a lean system there is less safety stock, or extra inventory, to cope with disruptions, and a minor disruption has the potential to shut down the entire supply chain (Sheffi 2005). Enterprises that operate just-in-time (JIT), in which supplies or components arrive at almost the exact time they are needed instead of being held in inventory, are vulnerable to transportation disruptions when goods are delayed.

3.2 LITERATURE REVIEW

Literature regarding the management of supply chain disruptions has become increasingly prevalent as the threat of disruptions has become more visible. Sources of information on the subject either take a broad approach to examining supply chain resiliency or focus on narrow topics such as supply and demand disruptions, developing relationships, physical and digital security, and organizational culture. Here we summarize the literature in the areas most relevant to this work: supply chain resiliency, supply and demand disruptions, external disruptions, resilience culture, and network structure.

3.2.1 Supply Chain Resiliency

The Resilient Enterprise (Sheffi 2005) was a comprehensive overview of the changing focus of supply chains in a post-September 11th world. Sheffi explained the importance of resiliency, explored potential vulnerabilities in supply chains, and introduced ways to decrease vulnerability and increase flexibility (as a means of increasing resiliency) through improved supplier relationships and communications, collaborative security efforts, and flexible production operations. Pickett (2003) examined past disruptions, including earthquakes, hurricanes, floods, accidents, labor strikes, and terrorist attacks, to understand the impact they had on supply chains. The study of these past events yielded lessons about preparation and reactions to future disruptions and provided recommendations to strengthen supply chains, reduce disruptions, and maximize resilience in the future. Christopher and Peck (2004) examined supply chain risks and suggested ways to create a resilient supply chain through supply chain risk management efforts such as re-engineering the supply chain to value resiliency, increasing collaboration between supply chain partners, focusing on agility, and developing a culture that embraces the risk management concept.

3.2.2 Supply and Demand Disruptions

Snyder and Shen (2006) discussed the management of disruptions to multi-location supply chain systems. They suggested that while the underlying issue with both supply uncertainty and demand uncertainty is having too little supply to meet demand, there are significant differences between the two uncertainties, and the optimal disruption management strategies take into account both types of uncertainties and their interaction. Hopp and Yin (2006) developed an analytical model to reduce the risk of "catastrophic" supply failures by balancing the cost of inventory and capacity protection to the cost of lost sales. Tomlin (2006) looked at supply uncertainty by using a mitigation and contingency framework to evaluate supply-side tactics such as sourcing mitigation, inventory mitigation, and contingency rerouting.

3.2.3 External Disruptions

Examining external disruptions exogenous to the supply chain, Kleindorfer and Saad (2005) developed a framework for identifying sources of, assessing, and mitigating external risk, such as natural disasters, economic disruptions, or terrorist activity. Rice and Caniato (2003) focused on disruptions at all levels of the supply chain due to terrorist activities and governmental responses to these potential threats. Through a series of interviews with firms in the United States, their research detailed corporate risk assessment and corporate response to recent terror activities, namely September 11th. Sarathy (2006) examined security and the supply chain, including governmental safety regulations, the connection between security and technology, and general suggestions for action to improve supply chain security.

3.2.4 Resilient Culture

Benson (2005) discussed the importance of organizational culture in resilient supply chains. Benson's study consisted of corporate interviews focusing on work infrastructure and practices, human resources practices, education, communication, and measurement systems to examine enterprise policies and how they affect security and resiliency of supply chains.

3.2.5 Network Structure

Focusing on network structure and the impacts of disruptions on costs and flow over the network, Latora and Marchiori (2005) discussed a method of finding the critical components of an infrastructure network. These nodes and links, which are fundamental to the perfect functioning of the network, are the most important to protect from disruptions such as terrorist attacks. Snyder et al. (2006) discussed models for planning supply chain networks that are resilient to disruption. These models attempt to design supply chain infrastructure that will operate efficiently and at low-cost during times of both normal and disrupted operations.

3.3 DATA AND RESEARCH METHODOLOGY

The research presented describes how enterprises are addressing supply chain resilience through resilience strategies. This supply chain behavior is necessary to understand in the context of freight transportation system resilience, as the users and their behavior are key elements of the system and determine system performance. This research not only provides a summary of existing strategies being used but also presents a framework and common language for discussing resiliency. Understanding the implications of employing various enabler and resiliency strategies can assist managing organizations in understanding how supply chains adapt and accommodate disruption.

3.3.1 Data Sources

Data on resiliency strategies used were gathered through ten informational interviews conducted with personnel responsible for transportation activities and operations in enterprises spanning a broad range of industries. In addition to being responsible for daily supply chain and transportation operations, many interviewees also took part in strategic decision making regarding the transportation system of their enterprise's supply chain.

As required by the University of Washington Human Subjects Division, confidentiality of the interviewees and enterprises was maintained by generalizing key attributes of each enterprise. Enterprises are referred to as Enterprise A through Enterprise K, as seen in Table 3.1.

Table 3.1 Enterprise descriptions

Enterprise	Industry*	Annual Sales Range ($ billion)*	Goods Value	Perishability	Leanness	Technology
A	Retail	1-10	Low/Mid	Mid	Mid	Mid
B	Retail	50-100	Low	Mid	Mid	Mid
C	Retail	1-10	Low/Mid	Mid	Low	Low
D	Retail	50-100	Low/Mid	Mid	Mid	Mid
E	Food/ Beverage	1-10	Low	High	Mid	Mid
F	Food /Beverage	NA	Low	High	Mid	Mid
G	Chemical	0.1-0.5	Mid/High	Mid	Mid	High
H	Mfg.	10-50	High	Low	High	High
I	Mfg.	50-100	High	Low	High	Mid
J	Mfg.	NA	Mid/High	Low	Mid	Mid

**Source: Hoovers, Inc.*

Enterprises interviewed were characterized by six attributes. Industry sectors were generalized as Chemical, Retail, Food and Beverage, and Manufacturing. Enterprises D and E operated in multiple industry sectors with the dominate sector listed in Table 3.1. Industry sector and annual sales information was gathered from Hoovers, Inc. (http://premium.hoovers.com). The four remaining attributes reflect characteristics of enterprises. Relative values of these attributes were based on information gathered both directly and indirectly from interviews and were assigned by the author.

3.3.2 Research Methods

As previously mentioned, ten exploratory interviews were conducted in this study. Interview questions were related to transportation priorities, vulnerabilities, and supply chain resiliencies. The interviews were semi-structured with a prepared set of questions, all of which were not necessarily asked of each interviewee. This research focused on an enterprise's perception of its resiliency in addition to its actual resiliency strategies; therefore interviewees were not asked directly which resiliency strategies they did or did not employ. In some instances, what an interviewee did *not* say also provided valuable insight, such as into the enterprise's level of resiliency maturity. The information both provided and absent from interviews was used to draw conclusions about enterprise resiliency. Additional questions were asked to clarify, elaborate, or further discuss, as necessary.

The qualitative data collected during the interviews provided insight into the resiliency strategies being used by interviewed enterprises but did not provide a basis on which to draw universal conclusions about supply chain resiliency. This research did not attempt to document the entire set of strategies used across all enterprises engaged in the movement of goods, or their frequency of use, which would require a more comprehensive sample, but instead focused on company perceptions of effective resiliency strategies, the relationships between resiliency strategies and between strategies and enablers, and the relationship between resiliency strategies and other company attributes.

3.4 DEFINITIONS

3.4.1 Supply Chain

As defined by Christopher and Peck (2004), a supply chain is "the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer."

Resiliency strategies may be utilized at most points along the supply chain, but this research focused on resiliency within the goods movement segment of the supply chain.

3.4.2 Disruption

An event that has the potential to cause a temporary and undesirable impact to the goods movement within a supply chain.

3.4.3 Resiliency Strategy

Resiliency strategies are employed by enterprises to reduce the exposure to or mitigate the impacts of disruptions to the supply chain. For the purposes of this research, resiliency strategy was defined as an action undertaken with the intent to reduce the occurrence or mitigate the effects of disruptions, allowing a supply chain to maintain or return to normal operating conditions.

3.5 RESILIENCY STRATEGIES

Interview questions inquired about vulnerabilities within the supply chain, resiliency within the supply chain, and procedures used to handle disruptions. From the information gathered during the interviews, 15 resiliency strategies were identified. These strategies were both directly and indirectly identified by enterprises. If an enterprise did not report a strategy, it can be assumed that (1) the enterprise did not practice the strategy, (2) the enterprise did employ the strategy but did not find it significant to its resiliency efforts, or (3) the enterprise did employ the strategy but failed to mention its use because it had become commonplace within supply chain operations.

Strategies were categorized as being either enablers or tactics. Enablers were defined as those that do not directly improve resiliency but instead facilitate the success of tactics. They enable or encourage resiliency. The majority of strategies were characterized as tactics, as they were tactical decisions. The resiliency strategies identified within the interview process are listed in Table 3.2.

The following explanations and evaluations of strategies consist of a combination of perceptions gathered by the author at interviews and research interpretations.

Table 3.2 Identified resiliency strategies

STRATEGIES	CATEGORY	REPORTED BY (ENTERPRISES)
Relationships	Enabler	A, D, F, G, J
Use of Information & Technology	Enabler	B, D, G,H, I
Communication	Enabler	A, B, D,F, G
Flexible Culture	Enabler	A, F, H
Flexible Transportation	Tactic	A, F, G, H
C-TPAT Certification	Tactic	A, E
DC Structure, Size of Network	Tactic	D,E, H
Resilient Nature of Suppliers	Tactic	F
Expedited Freight	Tactic	A, D,H, I
Use of Multiple Ports/Carriers	Tactic	B, E, H
Employees Overseas	Tactic	B
Extra Capacity at DC	Tactic	C
Off-Peak Deliveries	Tactic	E
Domestic Sourcing	Tactic	E
Premium Transportation	Tactic	H, I, J

3.5.1 Enablers

Enabler strategies do not directly reduce or mitigate disruptions. Instead, enablers often help identify disruptions and lead to further action or aid in response to a disruption. Four enablers were identified during the interviews.

3.5.1.1 Relationships

Definition: An enterprise develops and maintains relationships with suppliers, carriers, and customers in the belief that strong relationships will result in increased assistance and flexibility during disruptions.

Evaluation: As an enabler, developing strong relationships improves resiliency by making partners more likely to aid an enterprise when a disruption occurs in order to continue to do business. A strong relationship could both reduce the potential for disruptions to affect a supply chain and mitigate the impacts of a disruption that does have an effect on a supply chain. Beyond having a strong relationship, action must be taken to avoid or mitigate the disruption, which often occurs in the form of an additional resiliency strategy such as flexible transportation, described later. Strong relationships do not guarantee that partners can or will act in the best interests of the enterprise in the face of a disruption.

3.5.1.2 Use of Information and Technology

Definition: An enterprise gathers information, generally through increased technology, to manage disruptions. Tools such as transportation management systems (or similar enterprise management software) and procurement agents may help track goods and detect potential or actual disruptions.

Evaluation: The use of information and technology improves resiliency by gathering and presenting information about disruptions. This can occur by increasing the amount and level of detail of information available, making information easily accessible, providing information to all members of the supply chain, and providing information in a timely manner. Information can provide knowledge of a disruption and gives an enterprise the opportunity to act to avoid or reduce the effects of the disruption. As with relationships, an action must be taken, beyond the gathering of information, in order to improve resiliency.

3.5.1.3 Communication System

Definition: An enterprise develops and maintains a robust and reliable communication system to relay information, gathered previously, about supply chain status to those who have the authority to take action in order to prevent or mitigate disruptions.

Evaluation: Robust and reliable communication systems improve resiliency by enabling a transfer of knowledge about a disruption between parties within the supply chain. Having knowledge of a disruption gives an enterprise the opportunity to act to avoid or reduce the extent of damage. As with relationships, an action must be taken, beyond the delivered communication, in order to improve resiliency.

3.5.1.4 Flexible Culture

Definition: Flexible culture involves developing a business environment that encourages and promotes innovative and creative ideas to improve supply chain resiliency and resiliency practices.

Evaluation: Enterprises with flexible cultures are more aware of the potential for disruptions and more likely to implement additional resiliency strategies. Key traits of enterprises with flexible culture include extensive communication between informed employees, distributed/decentralized power, a passion for the work, and experience with/conditioning for disruptions. Like the previous enablers, flexible culture encourages activities that reduce exposure to or mitigate the impacts of disruptions.

3.5.2 Tactics

Tactics are typically part of an enterprise's ongoing business culture and process, as well as included in companies' business continuity plans, and are implemented on both a day-to-day and as-needed basis. Eleven tactics were identified and are examined below.

3.5.2.1 Flexible Transportation

Definition: An enterprise has the ability to make last-minute changes to transportation providers, routes, or schedules in case of disruption.

Evaluation: Flexible transportation policies have the ability to help an enterprise both avoid exposure to disruptions and mitigate the impacts of disruptions. Examples of using flexible transportation to improve resiliency include using detours to avoid disruptions, changing delivery schedules, and having backup carriers, such as out-of-region carriers, to reduce the effects of a disruption that affects primary carriers.

3.5.2.2 C-TPAT Certification

Definition: An enterprise is Customs-Trade Partnership Against Terrorism (C-TPAT) certified in the belief that this status will reduce or mitigate disruptions. C-TPAT is a voluntary government-business initiative that aims to improve U.S. border security.

Evaluation: Given the benefits of C-TPAT compliance, including reduced inspections and priority after a port shutdown, participation can both reduce exposure to disruptions and mitigate the effects of disruptions. Disruptions caused by inspection delays are reduced because C-TPAT-certified enterprises are less likely to undergo an inspection. Impacts of disruptions such as port closures are mitigated by providing C-TPAT-certified enterprises with priority to get freight out of the ports as soon as possible after an event.

3.5.2.3 Distribution Center Structure, Size of Network

Definition: An enterprise has a network structure that has the ability to serve, on short notice, a destination/store from a different distribution center than typically served in order to handle product shortages due to disruptions.

Evaluation: Having a large network allows an enterprise to avoid or mitigate the effects of disruptions by moving products around as needed with more flexibility. If final destinations (stores) are located close to several distribution centers and inventory is available, distribution patterns can be modified to react to potential or actual disruptions in a timely manner. An enterprise has the ability to route around problems.

3.5.2.4 Resilient Nature of Suppliers

Definition: An enterprise does business with resilient suppliers in order to improve overall supply chain resiliency.

Evaluation: When resilient supply chain partners encourage an enterprise to increase its own resiliency in order to improve overall supply chain resiliency, this strategy is successful and helps an enterprise to avoid or mitigate the effects of disruptions. The supplier and the enterprise are often both vulnerable to the same risks.

3.5.2.5 Expedited Freight

Definition: An enterprise, upon identifying a disruption, uses accelerated freight transportation to move additional freight or to speed up delivery of an existing shipment.

Evaluation: Expediting freight mitigates the effects of a disruption by reducing the magnitude of a disruption. If a disruption occurs within the supply chain, a shipment may shift to an accelerated mode of transportation to make up for time lost in early segments of the supply chain, or a second shipment may be sent via accelerated mode.

3.5.2.6 Use of Multiple Ports/Carriers

Definition: An enterprise imports goods through more than one port or using multiple carriers as part of regular supply chain operations in order to avoid having a disruption affect the entire supply chain.

Evaluations: Using multiple ports and/or carriers can both reduce exposure to and mitigate effects of disruptions. Assuming that the likelihood of disruptions along multiple paths is small when goods move to a single destination port via multiple carriers, a larger percentage of goods is likely to reach its destination on time. While using multiple ports and/or carriers can improve resiliency, it also results in increased risks. When additional ports are included in a supply chain, an enterprise takes on the extra risks associated with importing into the new port, which may be distinct from risks at currently used ports, and therefore extra risk must also be accounted for in additional resiliency planning.

3.5.2.7 Employees Overseas

Definition: An enterprise locates employees overseas, in locations that are part of the supply chain, to oversee and manage operations.

Evaluation**:** Assuming that direct and frequent communication is more efficient and less error-prone than communication that takes place via technology (e.g., phone, e-mail, and internet), this strategy improves communication and may act as a catalyst for additional action. Locating employees overseas means that they are in closer contact with the suppliers/carriers while still reporting directly to the enterprise. There is also a presumed benefit of local knowledge that can be utilized by overseas employees.

3.5.2.8 Extra Capacity at Distribution Centers

Definition: An enterprise scales distribution centers to have a greater capacity than required for current volumes of goods moving through the distribution center in order to increase the ability to hold inventory as needed to improve resiliency.

Evaluation: Having extra capacity at distribution centers does not reduce exposure to or mitigate the impacts of disruptions. While extra capacity at a distribution center allows for holding more inventory, which increases resiliency by mitigating the impacts of a disruption, the extra capacity alone does not increase resiliency. This strategy helps improve resiliency through redundancy.

3.5.2.9 Off-Peak Deliveries

Definition: An enterprise delivers goods during off-peak hours to distribution centers or stores to avoid delivering at times when the risk of disruption is higher (e.g., peak traffic hours).

Evaluation: Making local, urban freight deliveries during off-peak hours reduces exposure to disruptions. For example, making deliveries during times when congestion is minimal reduces the risk of disruption or delay due to congestion.

3.5.2.10 Sourcing of Components Domestically

Definition: An enterprise acquires components/goods from domestic suppliers instead of from suppliers overseas (where they may be cheaper) because of a reduction in the likelihood of disruption in transit.

Evaluation: If you assume that the longer the supply chain, the more potential for disruption, then shortening a supply chain by sourcing domestically will reduce exposure to disruptions. Sourcing a component domestically removes ocean travel, movements through two ports, and dealings with customs and border protection. This resiliency strategy is most effective for goods that are critical to operations of an enterprise, such as a component whose unavailability would stop a production line or a product with no reasonable replacement.

3.5.2.11 Premium Transportation

Definition: An enterprise uses a more expensive mode of transportation, assuming that it offers a service that is more reliable or can move goods in a more efficient fashion.

Evaluation: Using premium transportation both reduces exposure to and mitigates the impact of disruptions. Carriers providing premium service often offer guarantees on the level of service. For example, in return for paying more to ship goods upon priority trains, shippers are guaranteed to have their goods moved to the front of the line if a disruption occurs that halts movement for a period of time—thus reducing the effects of the disruption. Premium transportation such as pre-planned air freight often has better visibility than other modes of transportation, allowing disruptions to be spotted easily.

3.6 DISCUSSION

3.6.1 Outcomes

There are two distinct outcomes to the implementation of resiliency strategies: (1) reduction of exposure to or frequency of disruptions and (2) mitigation of the impacts, or size and severity, of disruptions. A given strategy can both reduce and mitigate, depending on the circumstances of the disruption.

The distinction between reduction and mitigation is most clearly seen temporally. Reduction is proactive, and action is taken before the disruption physically affects the supply chain. Mitigation is reactive and occurs when exposure to the disruption cannot be avoided. The supply chain is affected by the disruption, and the resiliency strategy serves as a means of returning the supply chain to previous, or normal, operations.

All of the identified strategies can be considered strategic decisions, although many are employed operationally. For example, a decision to use multiple ports to import goods is made at a strategic level, as is the decision to allow goods movement to shift between ports as necessary and as capacity allows. However, the decision to actually shift goods from one port to another is made on an operational basis as events develop. Likewise, it is a strategic decision to allow expedited freight transportation to be used when needed, but the decision to send goods via an expedited service is made on a day-to-day basis.

Risk is spread temporally by using strategies such as flexible transportation, that is shipping goods ahead of or behind schedule to avoid potential disruptions. Risk can also be spread geographically by using strategies such as shipping to or from multiple ports and spread through personnel in by using strategies such as employing workers overseas.

3.6.2 Relationship to Current Operating Environment

The enterprises interviewed fell into three general business sector categories: manufacturing, retail, and food/beverage. In examining the strategies utilized by each enterprise, it became apparent that resiliency strategies are less likely to be linked to the specific nature of the business than to the maturity and natural likelihood for disruptions within the supply chain. As a supply chain develops and matures, it responds to frequent problems of the environment in which the enterprise operates. These responses often double as resiliency strategies. An enterprise may not directly identify certain strategies, such as enablers, when discussing resiliency efforts because these strategies have become commonplace to operations. The strategies reported are often a reflection of the maturity of an enterprises' experience with disruptions. Enterprises that are prone to disruptions, even those unrelated to transportation, develop a resilient supply chain and are therefore more resilient to transportation-related disruptions. Table 3.3 summarizes the strategies directly indicated by enterprises during the interviews.

Table 3.3 Interview reported strategies

STRATEGY \ ENTERPRISE	A	B	C	D	E	F	G	H	I	J
Relationships	■			■		■	■			■
Information & Technology		■		■			■	■	■	
Communication	■	■		■		■	■			
Flexible Culture	■					■		■		
Flexible Transportation	■					■	■	■		
C-TPAT Certification	■				■					
DC Structure/Size of Network				■	■			■		
Resilient Nature of Suppliers						■				
Expedited Freight	■			■				■	■	
Use of Multiple Ports/Carriers		■			■			■		
Employees Overseas		■								
Extra Capacity at DC			■							
Off-Peak Deliveries					■					
Domestic Sourcing					■					
Premium Transportation								■	■	■

Enterprise A, Enterprise B, and Enterprise D were classified as retailers, and while all three made use of enablers, other strategies that they utilized varied widely. Within the retail sector there is a large diversity of businesses and business models, meaning that each supply chain has different resiliency needs. The enterprises interviewed did not operate supply chains that were exceptionally lean or volatile. Instead, these enterprises understood, in the general sense, that resiliency can benefit a supply chain and chose to explore how resiliency could best be implemented within their own supply chain to address their specific needs.

Enterprise C had not experienced major disruptions and had few to no resiliency strategies in place. The rapid and recent growth of Enterprise C had left its supply chain scrambling to catch up. Because of the lack of previous disruptions, the supply chain decision makers did not perceive future disruptions as a large threat. Enterprise C had chosen to focus on expanding and increasing the efficiencies of its supply chain without seriously considering the importance of resiliency. Additionally, because of the lower cost of goods produced, Enterprise C could afford to hold more inventory than enterprises with higher cost goods such as Enterprise I and Enterprise H. This allowed Enterprise C to improve resiliency through the redundancy of extra inventory.

Enterprise E operated in the food and beverage business sector and primarily produced commodities to be consumed upon purchase. As with other commodities, if Enterprise E cannot deliver a product, another enterprise is able to provide a very similar one, impacting its sales. A small number of components are used to make a limited number of products, and if inbound shipments are delayed, the company stops production. Because the components are perishable and there is limited storage space in its facilities, inbound deliveries are made on a near-daily basis. The frequent delivery required for perishable, typically food and beverage, products means more exposure to disruption because of more overall time in transit. Enterprise E had developed a mature resiliency approach because of the likelihood of disruption, the severe consequences of disruption, and high competition associated its supply chain and operations. The strategies employed by Enterprise E, such as sourcing many critical components domestically and making off-peak deliveries, illustrate this maturity. While these strategies were not initially implemented to improve transportation resiliency, they did improve the enterprise's ability to minimize or mitigate transportation disruptions.

Enterprise F also provided food products, but displayed less resiliency maturity than Enterprise E because of a previous lack of experience with disruptions. Having a domestic supply chain reduced the potential for disruption and may have been a reason for Enterprise F's lack of experience with disruptions. A recent weather disruption, and subsequent breakdown within the supply chain, encouraged Enterprise F to evaluate and improve its resiliency procedures. As a relative newcomer to the area of resiliency, Enterprise F was beginning to integrate more general resiliency strategies, such as communication, relationships, and flexibility, into the supply chain. When faced with a second weather disruption a year after the first, Enterprise F utilized recently established strategies and reported that its supply chain response had improved as a result of the strategies in place. One can expect that as Enterprise F continues to explore and understand the importance of resiliency within its supply chain, the strategies it chooses to implement will be similar to those of Enterprise E. Enterprise F's actions align with other research that has concluded that enterprises that have experienced a previous disruption are more likely to be proactive in an attempt to improve resiliency (Rice and Caniato 2003)

The large manufacturing enterprises H, J, and I, utilized similar strategies, such as use of information and technology, expedited freight, and premium transportation, but they did not employ these strategies solely for the sake of resiliency. Both Enterprise H and Enterprise I manufactured expensive products by using a JIT strategy, meaning that the precise delivery of goods is essential to being able to operate with minimal inventory. While JIT is foremost an inventory strategy, its success hinges on the ability to operate with low volumes of inventory and still keep assembly lines moving. By removing safety stock, a supply chain is automatically less resilient and depends more on the reliability of other aspects of the supply chain, such as the transportation network. A JIT supply chain needs to actively increase resiliency and be able to respond to delays in order to be successful. Given the size and value of the goods produced by both these enterprises, the extra expenditures required to implement information technology systems and use expedited and premium freight were inconsequential in relation to the costs of holding increased inventory and potential assembly delays. Enterprise J did not operate as a JIT supply chain but provided products to enterprises that highly value expedited service. As with Enterprise H and Enterprise I, whose manufactured goods cost close to a hundred thousand and a hundred million dollars, respectively, the cost of transportation was negligible in comparison to the cost of customers' delays of business due to delayed goods. Like Enterprise J, Enterprise G provided products to enterprises that operate JIT and therefore value high levels of service. Higher value goods incur high inventory costs, and therefore it is most efficient to produce finished goods to be sold as quickly as possible.

A supply chain that operates with a JIT strategy can also be considered mature because of concerns that reach beyond solely ensuring that goods arrive at the destination as expected. Enterprises using JIT have made the decision to improve efficiencies to an already established supply chain, thus reducing supply chain costs. Disruptions are more consequential within these supply chains, and therefore resiliency efforts are more established. The strategies most commonly reported by these enterprises are the most appropriate and effective means of establishing resiliency given the requirements of a large, JIT manufacturing supply chain. Within these industries, transportation resiliency exists because of the enterprises' desire to reduce costs and their previous experience and responses to disruptions.

3.6.3 Relationships among Strategies

Upon examination of the strategies, it was evident that some strategies complement, and may even be necessary to execute, other strategies. For example, the use of a distribution center structure as a resiliency strategy assumes the use of expedited freight in order to reroute products between distribution centers and stores in a timely manner. Additionally, a flexible transportation policy encourages the use of numerous other strategies, such as expedited freight, premium transportation, and use of multiple ports/carriers. While not mentioned as a strategy by interviewees, increased inventory is required to execute identified strategies such as distribution center structure and extra capacity at distribution centers.

Conversely, inconsistencies were also evident among the strategies identified during the interviews. For example, the strategy involving locating employees overseas is not compatible with the strategy to source domestically because one encourages operating globally while the other aims to avoid it. Therefore, note that not all of the strategies identified during the interviews can be implemented at once by one enterprise.

3.7 CONCLUSIONS

The enterprise view of supply chain resiliency cannot be isolated from the resiliency of the transportation system, which includes the physical infrastructure, government policy and regulations, and all transportation system users (such as private vehicles, commercial fleets, and public transportation vehicles). An enterprise can have extensive resiliency plans in place but most often still requires assistance in the form of information or infrastructure to successfully implement the plans. Supply chains are dependent on both public and private infrastructure, and often enterprises rely on governmental agency policies in order to move goods efficiently.

Much of the infrastructure on which goods move is designed, built, and managed by a department of transportation (DOT), whether at the city, state, or federal level.

Additional goods are moved on private infrastructure, such as rail, which is managed by private agencies. During normal conditions, enterprises know what to expect from and how to best use the infrastructure, primarily through experience. During a disruption, an enterprise's level of resiliency may depend on understanding how the infrastructure has been affected, what alternatives have been provided, and how other users respond. Additionally, if the agencies maintaining the infrastructure understand how enterprises use the infrastructure to move goods, they can make better decisions about how to handle disruptions in order to minimize the impacts on users.

From the strategies identified during the interviews, the following conclusions can be made about the impacts of these strategies on the transportation system. Broadly speaking, the transportation system benefits from efficient freight operations, as fewer vehicles miles and vehicle hours are spent producing the same good. Less infrastructure capacity is required to perform the same work of moving goods from origin to destination. Below we examine the impacts of the use of these strategies on the transportation system in more detail.

- Developing **relationships** with the agencies or personnel who manage the components of the transportation system helps facilitate communication and information sharing between the enterprise and the transportation system. With better information about user behavior, the agency can make better investment decisions regarding system operation and improvement.
- The **information** gathered by enterprises through technology, and then shared with the agency through **communication**, allows the agency to manage the transportation system more effectively.
- If an enterprise maintains a **flexible transportation policy**, the managing agencies can rely on the enterprise to be able to reroute around problem areas if given proper notice, relieving the stress or demand on these areas during a disruption.
- Gaining **C-TPAT certification** helps to facilitate security procedures within the port, assisting the port management agency in improving the efficiency and safety of cargo movement through the port.

- Having a wide-spread **distribution center structure** spreads the transportation demands of an enterprise over the infrastructure, lessening the burden on any one region or segment of the transportation system. Using **multiple ports or carriers** also achieves this end.
- When an enterprise **delivers during off-peak hours**, it utilizes the infrastructure at a time when there is typically excess capacity and reduces demand on the transportation system during peak flow periods. This allows the transportation system to provide better service to other uses.
- An enterprise that **sources domestically** may increase the demand for domestic transportation but decrease the burden on U.S. points of entries such as ports. The net effect depends on the relationship between current demand and capacity of these system elements.
- Finally, some forms of **premium transportation** demand a higher level of service from the managing agencies in the event of a disruption.

In general, the use of resiliency strategies by enterprises also increases the resiliency of the transportation system. We expect that many enterprises will adopt additional resiliency strategies. Overall, these will improve the level of communication between parties active in the transportation system and will help spread demand for the transportation infrastructure across time and space.

In the interviews, enterprises expressed some concern regarding government responses to disruption. Historically, the government response to disruptions has in some cases had a greater impact on supply chains than the disruption itself. For example, the closure of U.S. airspace and delays at the borders immediately following the attacks on September 11th were more disruptive to supply chains than the actual attacks themselves (Rice and Caniato 2003). With regard to both large-scale and daily disruptions, the policies of federal, state, and local governments affect an enterprise's ability to move goods. These policies include federal policies such as C-TPAT and the Container Security Initiative (CSI), as well as local policies such as hazard mitigation plans. From the enterprise's perspective, it is important to understand and anticipate government reactions to disruptions in order to improve resiliency. The most successful government policies are those that are embraced by industry, and they are product of an interaction between the enterprises and agencies.

In the interviews conducted, several enterprises voiced concerns about interactions with governmental agencies. Enterprise A, Enterprise D, Enterprise E, and Enterprise J identified security measures such as the Customs and Border Protection's 10+2 initiative and the Transportation Worker Identification Credential program as potential transportation challenges. Enterprise J commented that since September 11th, the Department of Homeland Security and the Transportation Security Administration have made commerce more difficult. Enterprise E remarked that it understood the purpose of such initiatives but felt that they were difficult to comply with. Enterprise H identified border controls, especially at the southern border, as an issue. Being required to switch trucks, and often carriers, at the border introduces more room for disruption or incident within the supply chain. These initiatives have been implemented to deter disruptions and protect trade, but they also introduce challenges to supply chains.

With regard to both infrastructure and policy, successful interactions between the private and public sectors require communication and information exchange (both enablers) to occur before, during, and after the disruption. To effectively accomplish this exchange, relationships (another enabler) must be developed between the two entities. In addition, we have observed that enterprises that are the most prepared for disruptions are the ones that experience them most frequently. Public sector agencies would be more effective not by suggesting that disruptions can be eliminated but in communicating with their users as effectively as possible. The fourth enabler, flexible culture, is also an important trait for a DOT to embody in order to best react to disruptions and interact with enterprises moving goods. Enterprise resiliency and systems resiliency are not stand-alone concepts, and interactions between the two are necessary for either to achieve resiliency.

4. A MULTI-MODAL STATE FREIGHT TRANSPORTATION NETWORK

A multi-modal state freight transportation network should represent the rail, road, air, and marine infrastructure (Figure 4.1). This is necessary as a framework for representing the flow of goods and for considering the impacts of changes to the infrastructure. In addition to representing the physical links, or connections, and nodes, or intersections and terminals, the network must also include some rules regarding the cost of travel along each link and through each node. Furthermore, some logical rules are required, for example, to differentiate overpasses from at-grade intersections. Early on in the project we decided on a methodology that took a bottom-up rather than a top-down approach to capturing goods flows on the infrastructure.

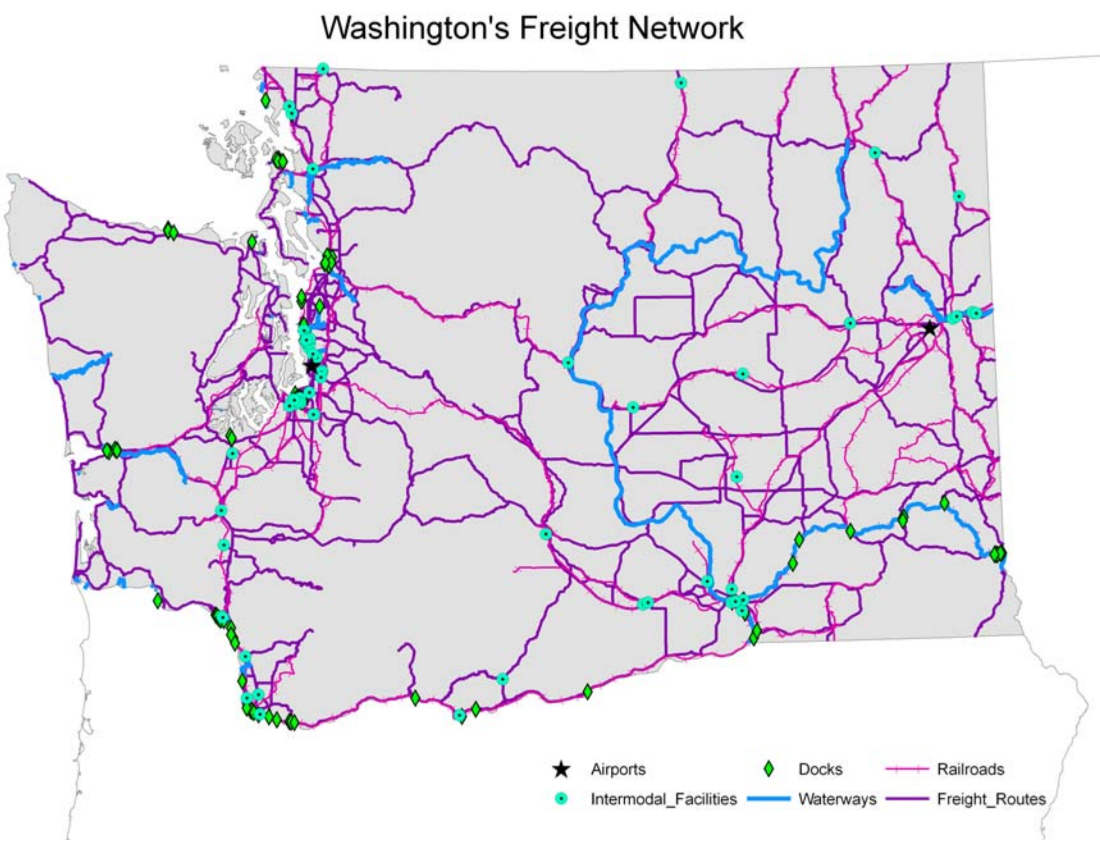


Figure 4.1 Multi-modal state freight transportation network

A geographic information system (GIS) was the clear preference for building the statewide transportation network. This format is the industry standard for spatial representations. A network consists of links, or line segments representing roadways or other linear transportation features, and nodes, or locations where these linear features connect, such as ports, terminals, and junctions. A GIS framework was selected, for which shapefiles were obtained for all modes. ESRI's ArcGIS 9.3.1 was selected as the GIS software to use. ESRI is the world leader in GIS modeling and mapping software. Historically, GIS analysts have approached multi-modal networking with sub-networks for each mode. In the traditional approach, transfers between modes are handled by psuedo-links or nodes. In the most recent versions of ArcGIS, these nodes comprise connectivity groups that participate in multiple subnetworks. Note, however, that traditional multi-modal networks have been built around passenger transit models. Passenger transit models are unique in that the transfers between modes (e.g., bus to rail) are typically highly predictable for two reasons: 1) there is a universal and easily calculated cost measurement—time, and 2) within-group variation in the time required for transfer is low.

By comparison, intermodal freight transfers are much more heterogeneous—some transfers require little processing and occur relatively quickly while others require significant processing and take comparatively longer. Even more importantly, logistics decisions balance the monetary costs against velocity and reliability. In the network, transfer nodes are not dynamic; they can only account for a single cost. Typically, network impedance, or the cost of travelling along a link or through a node, is calculated by using either distance or time, and in the case of a transfer node, impedance is typically given in time. While a logical model capable of integrating costs into the transfer nodes now exists within the ArgGIS database management system, there is no way to assign accurate impedances to the transfer nodes. This is the case because the willingness and ability to pass along the costs associated with velocity and reliability vary over time and across industries, and the variance can be extreme. For these reasons, modeling intermodal freight transfers requires timely data and a deep understanding of the needs and cost structures of the industry being modeled.

Early in the research process, we became aware of GeoMiler. GeoMiler is a GIS tool created by the U.S. Department of Transportation to model multi-modal freight traffic. Through a personal interview and numerous email interactions, we learned that the creation of the GeoMiler tool required a team of six technical FTEs employed for 14 months. Additional FTEs are required to maintain the database and use the tool. Given the tool's purported ability to model multi-modal freight shipments and the amount of person-hours required to build it, we felt that our early efforts would best be spent on acquiring GeoMiler rather than on countless hours duplicating these efforts. This required that we obtain data sharing agreements to use data that the USDOT did not create itself. These included data for the entire road network, which was purchased from Teleatlas.

The GeoMiler tool is capable of solving least cost routing problems on a multi-modal network if the following pieces of information are known: origin and destination (by zip code) and modal order (e.g., road-rail-road). Without the modal order, the tool is not capable of determining the most efficient combination of all possible modes and routes between any given origin and destination. Given the modal order, GeoMiler can calculate the most likely route taken by a shipper.

This can also be accomplished by using independent modal networks if the modal order is given. For instance, if one knows that a good from origin *i* follows a truck-train-truck modal order, the GIS analyst can simply use the nearest neighbor function to find the transfer facilities closest to the origin and destination. This method essentially generates three origin-destination pairs: 1) origin to closest transfer facility (which becomes the rail origin) via the road network, 2) rail origin to the transfer facility closest to the final destination via the rail network, and 3) transfer facility to the final destination via the road network. It is not possible in either approach to calculate the total time in transit without knowledge of the time necessary to transfer that particular amount of goods at each of the individual transfer facilities.

In this project, we utilized GeoMiler data, which were shared with us in the form of shapefiles. Understanding that our project required only Washington state rail, road, and waterway data, technicians at GeoMiler clipped the network datasets to a shapefile of

Washington state. This decision proved to be problematic. Each of the individual problems and their impacts are explained below.

1. By clipping the networks, a number of possible alternative routes were lost. Perhaps most problematic was the non-inclusion of I-84, but a number of alternative routes in Idaho were also clipped. These roads had to be rebuilt.
2. The clipping process also introduced a number of slivers to the road network. A sliver is a discontinuity along a network feature. These slivers, which only occurred on road segments located in close proximity to the state border, resulted from the clipping of the road network, which was accurate at a high spatial resolution, by a state shapefile of lower spatial accuracy. Heuristically, one can think of the road network as cookie dough, and the state shapefile as a cookie cutter. Because of the accuracy and resolution issues, some segments of Washington roads were lost in the clipping process, and these discontinuities had to be found and repaired.
3. For reasons unknown, the network elements were shipped to us not as a functioning network, but rather as a set of shapefiles. Shapefiles amount to little more than image files with some data attached. The network had to be rebuilt before any least cost routes could be calculated and for the network to function properly.
4. Before the network could be rebuilt, hundreds of “imaginary” roads had to be removed from the road shapefile. The GeoMiler tool was designed to route commodities from a zip code origin to a zip code destination. The original road network was purchased from Teleatlas—the same company that provides Google Maps with its road network. In order to streamline the GeoMiler tool, over 14 million miles of non-freight roads were deleted from the Teleatlas network. This introduced a new problem: how to deal with origins and destinations not located on the reduced road network. The solution was to build 'imaginary' roads connecting points located at the centroids of zip code polygons to the road network. In order to ensure that freight movements did not travel on these imaginary roads at any time other than when these imaginary road segments connected to either the origin or the destination, they

were assigned a cost that was an order of magnitude higher than the highest of the real road segments. Before the network could be rebuilt, hundreds of these imaginary roads were deleted from the road shapefile, given our preference not to route truck trips on these imaginary roads.

5. Special permission had to be granted by TeleAtlas for us to obtain and use the road network from the Bureau of Transportation Statistics (the producer of GeoMiler). Getting the attention of anyone at TeleAtlas to do so was time consuming.
6. No metadata were provided with the shapefiles that could be used to interpret costs and codes.

After each of these individual issues had been addressed, the resulting road network was reconciled with the WSDOT freight system. Through this process, a number of additional roads were added.

Building the network required that impedances be assigned. For the vast majority of road segments, impedances were inherited from the Teleatlas network. Because the GeoMiler data did not come with adequate metadata, it is impossible to know exactly how the cost field values were calculated. It appears that cost is a direct function of length and average speed. Regardless, this is the cost field that is used by Google Maps, so it is unlikely that it could have been improved for this project. Cost field values for the road segments that were redrawn were calculated by applying the ratio of the cost field to the miles field of the segment to which the new segment was being appended.

5. CASE STUDIES

To consider the flow of goods within Washington state, we begin by, in Figure 5.1, splitting freight flows into international, national, and intra-state flows (Alaska is separated because of its reliance on Washington state facilities). The size of the various elements are not based on the estimated volumes of these flows.

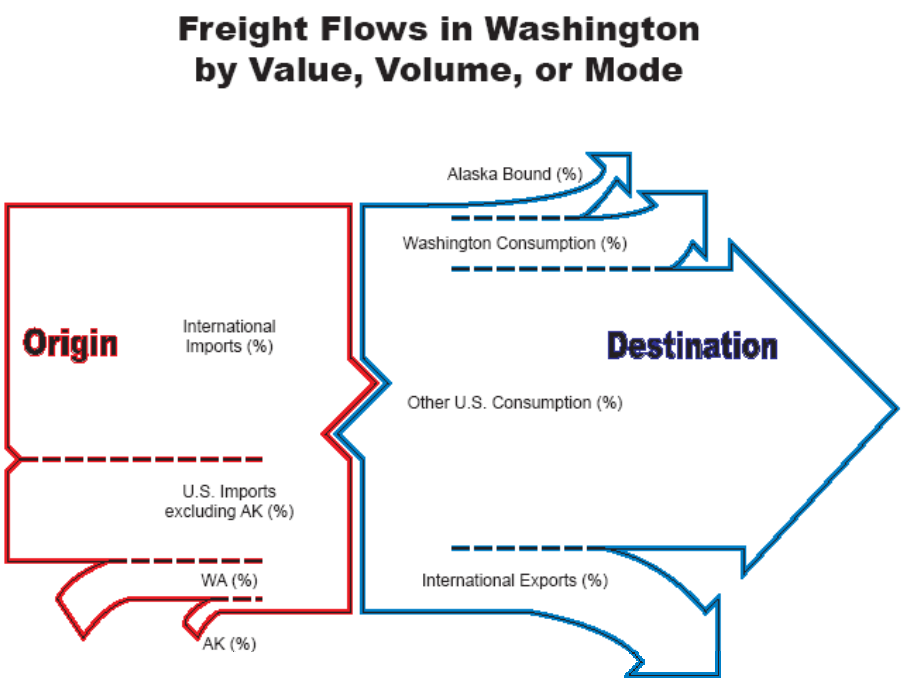


Figure 5.1 Washington state freight flows

Figure 5.2 shows the use of intermodal facilities by goods moving through Washington state, and Figure 5.3 shows the flow of goods within Washington state.

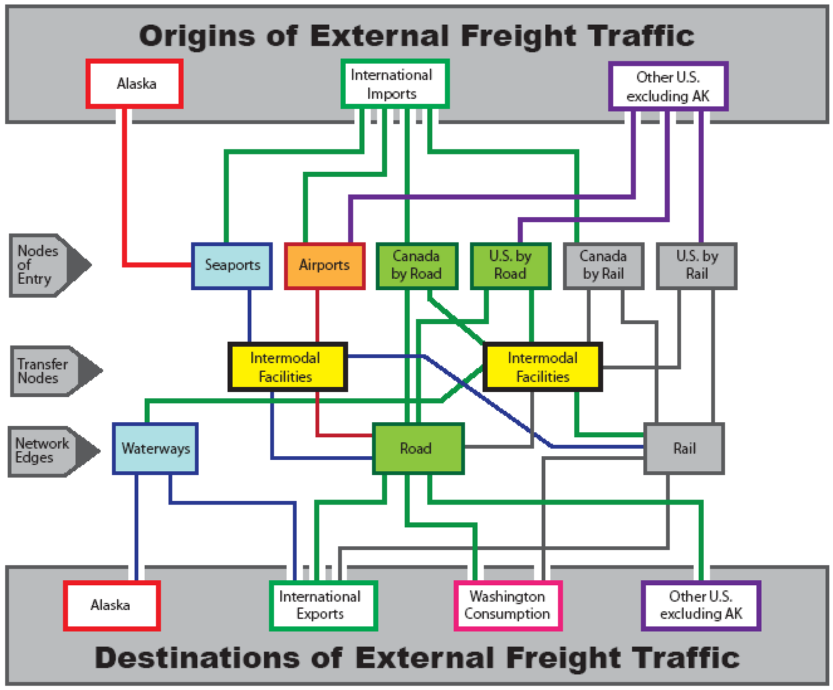


Figure 5.2 Flows of freight through intermodal facilities through Washington state

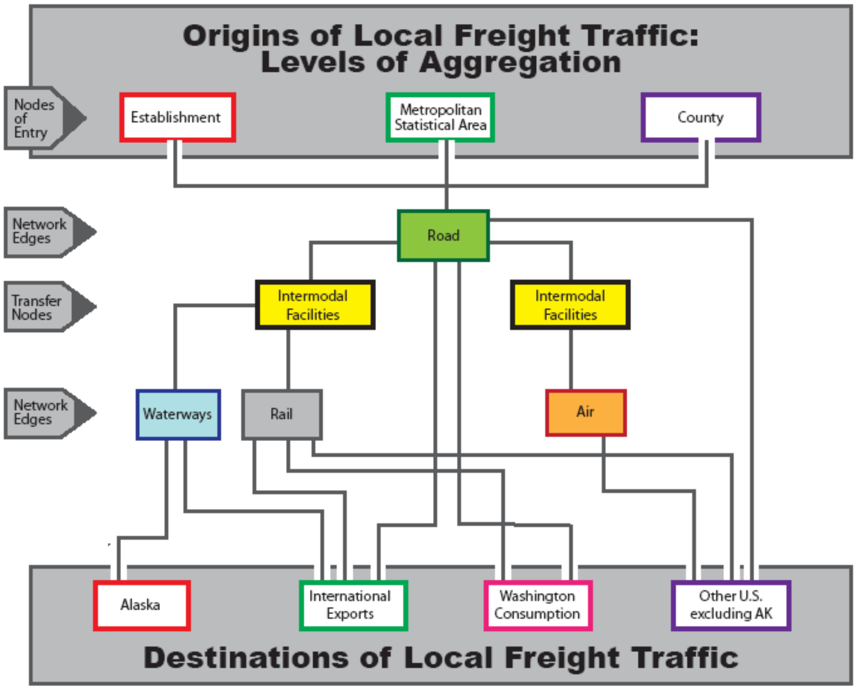


Figure 5.3 Flows of freight through intermodal facilities within Washington state

Breaking this down further, Figure 5.4 shows Washington state freight movements simply at the intra- and inter-state levels.

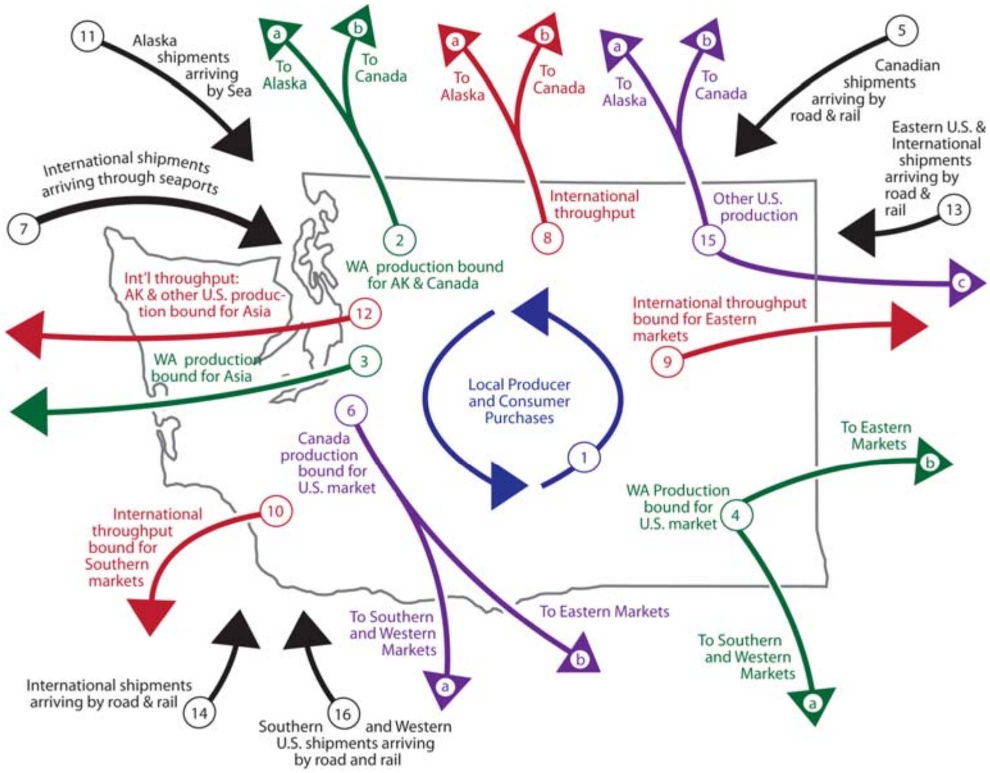


Figure 5.4 Intra- and inter-state freight flows

Figure 5.5 shows the dependence of these flows on intermodal infrastructure. Even at this aggregate level, the complexity of these flows can be conveyed. Statewide commodity flow data are not currently available in sufficient detail to meet WSDOT's objectives of modeling flows and their economic consequences at an industry level by transportation corridor. Given this, early on in the project we decided to not pursue aggregate data for all industries or geographic flows, but rather to collect and apply detailed, industry-specific flow data to the network model in the form of two case studies. We decided to evaluate the impacts of a one-day closure of the cross-Cascades passes on the Washington potato industry and the diesel distribution system.

DESTINATIONS \ ORIGINS	Washington	Alaska	Canada	Int'l*	Other U.S.
Washington	R, X(?), LW(?)	AW, R, X	AW, R, X	IW, A, R, X(?)	R, X
Alaska	R, AW	N/A	N/A	** IW, AW	** R, W, AW
Canada	R, X	** AW, R, X	N/A	** IW, R, X	** R, X
Int'l*	R, X, LW, IW, A	** AW, IW	N/A	N/A	** R,X, IW
Other U.S.	R, X	** AW, R, X	** X, R	** IW, R, X	N/A

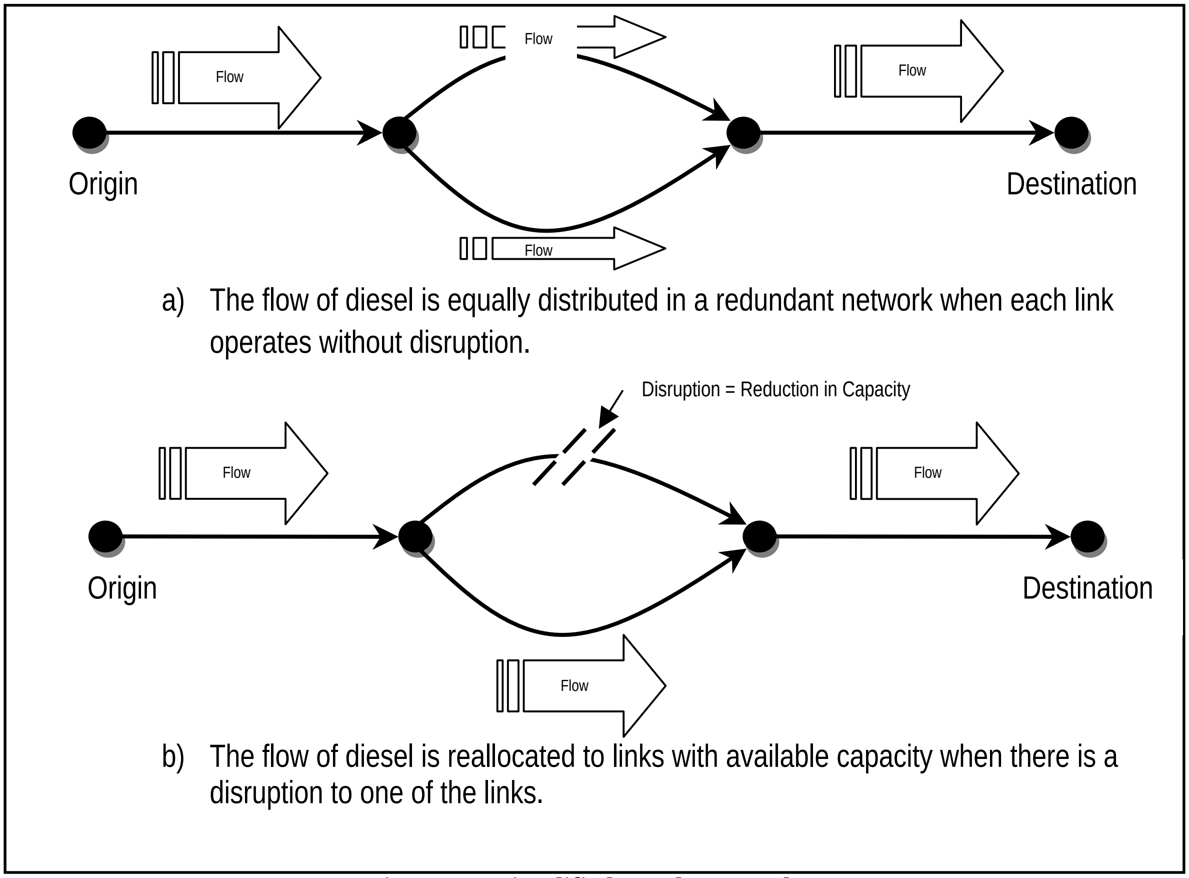
* Not including Canada
** Throughput

R = Road LW = Local Waterways
X = Rail AW = Alaska Waterway
A = Air IW = International Waterways

Figure 5.5 Dependence of freight flows on intermodal facilities

5.1 NETWORK

A network is a system of nodes and links that are connected in series or parallel (or a combination). Each node is a location for inventory or transfer and is either an origin or destination location for a trip between two individual nodes. A link is a connector and serves as the route for transportation between the nodes. The links accommodate flow between the origin and destination nodes and are restricted by the capacity along the route. A node that is connected by multiple links in the same direction is said to have redundancy because a trip has alternative routes from which to choose. A disruption (and thus a capacity reduction) along one of the links or at one of the nodes will cause a reallocation of the routes used by individual trips to accomplish an origin-destination journey. Figure 5.6 diagrams the flow of diesel on a network with redundancy, showing an equal distribution of flow on the redundant links, and then the result of the route re-allocation of flow during a disruption.



a) The flow of diesel is equally distributed in a redundant network when each link operates without disruption.

b) The flow of diesel is reallocated to links with available capacity when there is a disruption to one of the links.

Figure 5.6 Simplified supply network

Along a supply network there are two distinct types of disruptions:

1. Disruption to the transportation capability and thus reduction of supply chain capacity—this is analogous to a break in the link.
2. Disruption to a supply, storage, or production facility, thus reducing production and inventory capacity—this is analogous to a break at a node.

The severity of a disruption is a measure of the quantity by which the movement along the supply network is reduced from origin to destination. The measure of severity is affected by the capacity at which the distribution network is operating. If the supply system is operating at or near capacity, a disruption along any portion of the network will cause a reduction in supply capability. If excess capacity exists along the supply network, then it is possible that a disruption will have less of an effect on the ability of the diesel supply network to operate at an acceptable level. From this it can be concluded that some elements of the network may be considered more important than others.

5.2 POTATO CASE STUDY

By potato movements, we refer to estimates of daily vehicle level trips, for example, daily truck trips of fresh potatoes in the state. To identify the consequences of a disruption to potato movements, an understanding of existing potato movements is first required. This also includes capturing the variety of potato products, as well as the origins and destinations within the state.

A report completed for WSDOT and the Washington Potato Commission (Creamer, Selmin and Jessup 2008) proved very useful in providing the information required to estimate truck trips within Washington state.

5.2.1 Potato Production

Through previous work by Creamer et al., and as shown in Figure 5.7, it is clear that potatoes are produced in three regions of the state: the Skagit Valley, the Lower Basin, and the Upper Basin.

These three regions are considered origins of fresh potatoes. Centroids of the region are identified as the origins of truck trips. Potato production volumes are estimated from U.S. Department of Agriculture (USDA) field production data (Table 5.1).

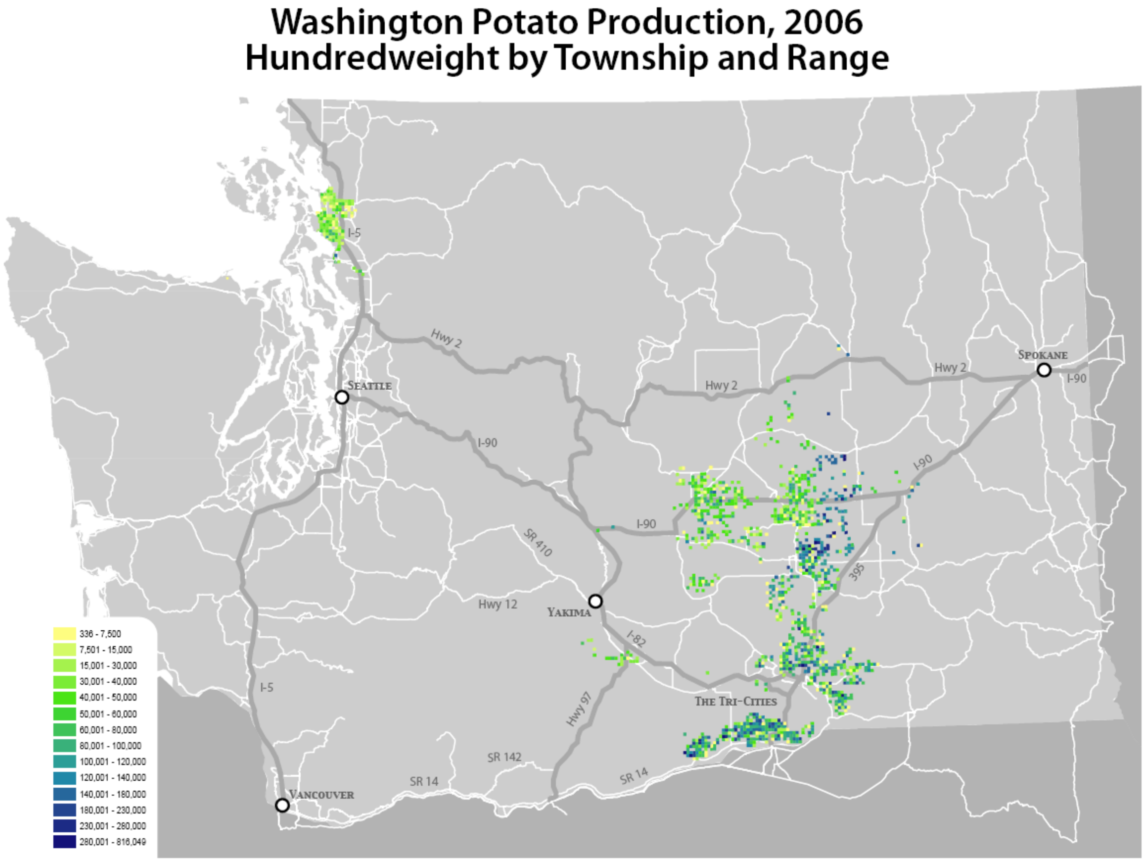


Figure 5.7 Washington potato production, 2006 from USDA field production data (Creamer, Selmin and Jessup 2008)

Table 5.1 Production volumes per region less recovery rate (USDA, Potato Commission)

	Total Production Skagit Valley	Upper Basin	Lower Basin
Production (Short Tons)	162,742	1,972,626	2,197,012
Recovery Rate	0.94	0.94	0.94
Total Purchased	152,977	1,854,268	2,065,191

On the basis of conversations with the Washington State Potato Commission, a capture rate of 94 percent was assumed in all regions. For each production region, percentages of potatoes sold fresh or processed were estimated on the basis of an "end of year comparison" from the Washington State Potato Commission (Table 5.2).

Table 5.2 Potato utilization by product for three production regions (Potato Commission)

Potato Utilization	Skagit Valley	Upper Basin	Lower Basin
Fresh	100%	14%	14%
Frozen	0	73%	73%
Dehy	0	11%	11%
Chips	0	2%	2%

5.2.2 Potato Processing

Potatoes are processed at 16 facilities within Washington state, as shown in Figure 5.8.

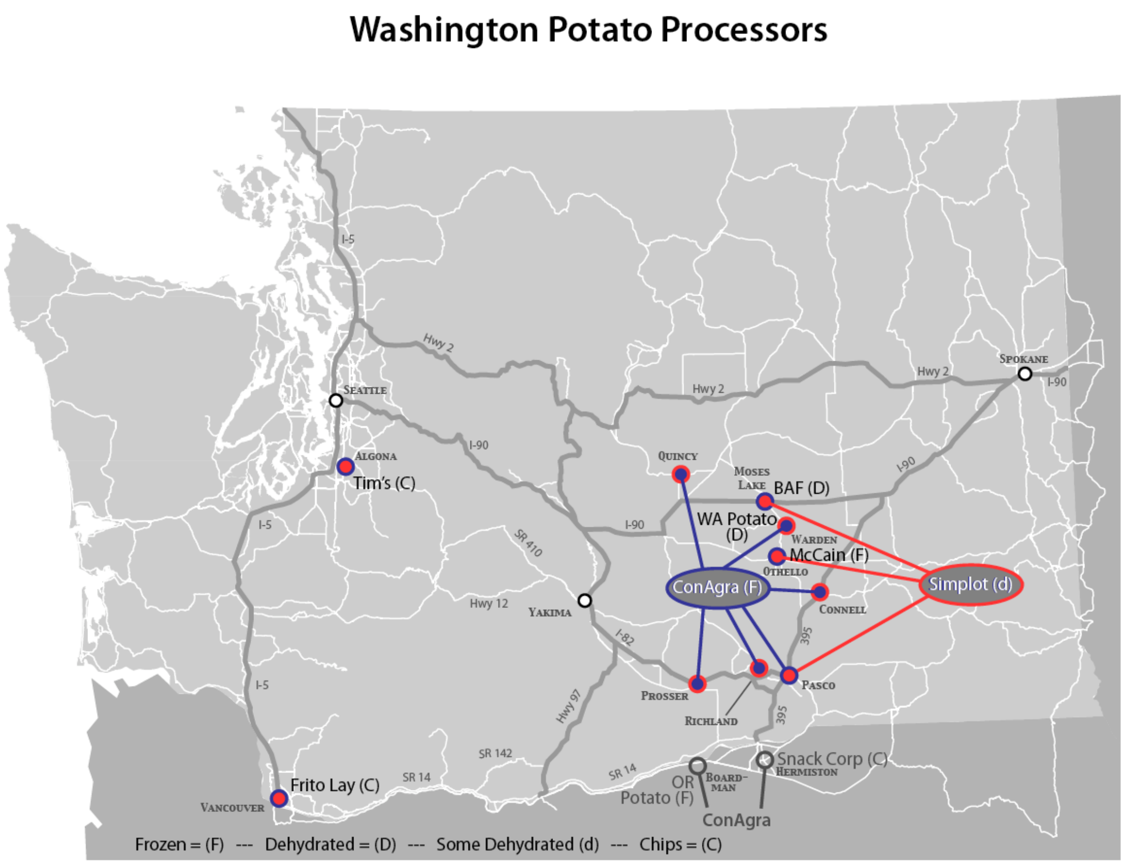


Figure 5.8 Potato processors in Washington state (Potato Commission)

Ratios of truckloads of fresh potatoes to truckloads of processed potatoes were estimated by the Washington State Potato Commission. The ratio for fresh potatoes is of course 1:1, and it is 2:1 for frozen potatoes, 4:1 for chips, and 6:1 for dehydrated potatoes. For example, for every truckload of dehydrated potatoes leaving a processing facility, six truckloads of fresh potatoes are required. Note, however, that a truckload of fresh potatoes is assumed to be equivalent to 22.22 tons, and a truckload of frozen potatoes is assumed to be equivalent to 20 tons.

No information was available regarding the location of dehydration for potatoes grown in the Skagit Valley. Dehydration could take place at processing facilities in either the Upper or Lower basins. On the basis of the expert knowledge of the Potato Commission, we estimated that 25 percent of these potatoes would be dehydrated in the Upper Basin, and 75 percent would be dehydrated in the Lower Basin. Potatoes grown in the Upper Basin were assumed to be processed in the Upper Basin, and potatoes grown in the Lower Basin were assumed to be processed in the Lower Basin.

5.2.3 Mode

We assumed that 25 percent of frozen potatoes processed in the state leave the state via rail. This was based on conversations with one of the state's largest frozen potato producers, ConAgra. We also assumed that 11 percent of fresh, dehydrated, and chipped potatoes are shipped out of the state on rail, given unpublished data from the Washington Potato Commission. Typically these potatoes are destined for regions east of the Mississippi.

5.2.4 Potato Consumption and Export

Potatoes grown and processed in the state are either consumed in the state or exported. The distribution of potatoes by destination given by the 2007 Potato Commission Survey is shown in Table 5.3.

Table 5.3 Percentage of shipments to major destinations by region (Potato Commission Survey)

Major destinations	Lower Basin	Skagit Valley	Upper Basin
Eastern Washington	12.48%	2.03%	6.22%
Western Washington	14.29%	6.81%	6.40%
Oregon	2.31%	4.35%	1.25%
California	14.58%	40.72%	11.85%
Idaho	0.00%	0.00%	34.33%
States west of Mississippi	22.01%	13.30%	12.76%
States east of Mississippi	24.26%	23.58%	11.99%
Canada	8.85%	7.04%	2.91%
Mexico	0.14%	1.96%	0.25%
Other international	1.09%	0.20%	12.03%

Potatoes destined to other international locations are exported via the Port of Seattle. According to the 2007 Potato Commission Survey, these shipments use the routes shown in Table 5.4. These truck trips are shown graphically in figures 5.9 through 5.11.

Table 5.4 Major routes used by region (Potato Commission)

Major Destinations	Lower Basin	Skagit Valley	Upper Basin
Eastern Washington	I-90, I-82, Hwy 12, 14	I-5, I-90, Hwy 2, 405	I-90, I-82, Hwy 17
Western Washington	I-90, I-82, I-5, 240, 395	I-5, 405, 167	I-90, Hwy 17
Oregon	I-90, I-82, I-84, Hwy 97, 395, 597	I-5	I-90, I-82, I-84
California	I-90, I-82, I-5, Hwy 97, 395	I-5	I-90, I-82, I-5, Hwy 17, 395
Idaho			I-90, I-82, I-84, SR 17, 395
States west of Mississippi	I-90, I-82, 395	I-90, I-80, I-5, I-84, 405	I-90, I-82, I-5, I-84, SR 17, 395
States east of Mississippi	I-90, I-82, 395	I-90, I-80, I-5, 405	I-90, I-82, I-5, I-84, SR 17, 395
Canada	I-90, I-82, I-5	I-5, I-90	I-5, I-90
Mexico	I-82, I-5, Hwy 97	I-5	

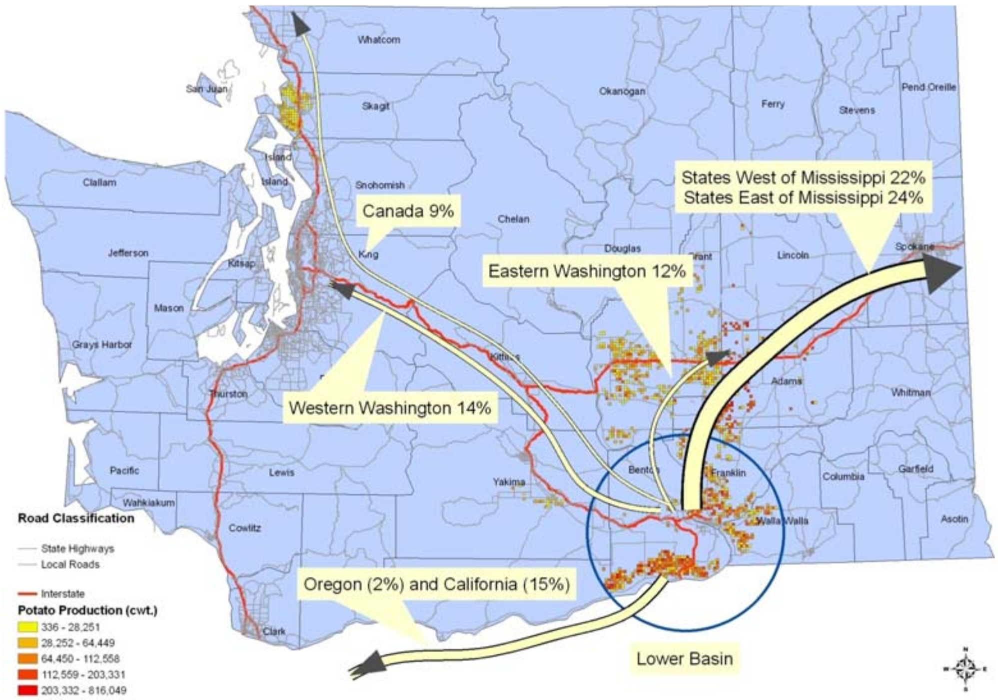


Figure 5.9 Shipment destinations for Lower Basin potato production (Creamer, Selmin and Jessup 2008)

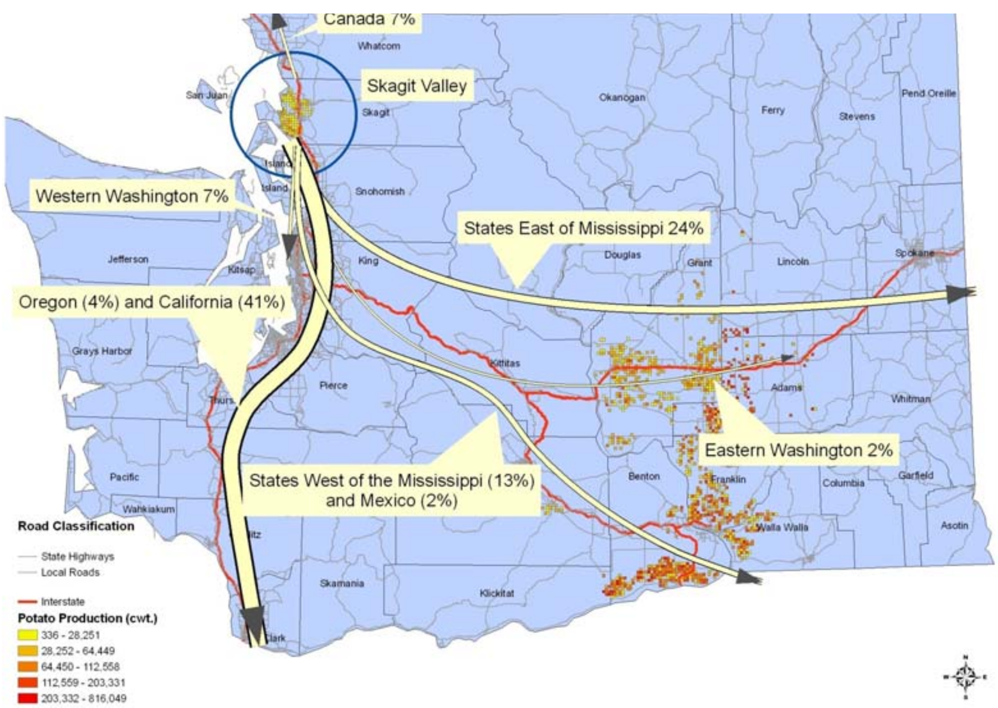


Figure 5.10 Shipment destinations for Skagit Valley potato production (Creamer, Selmin and Jessup 2008)

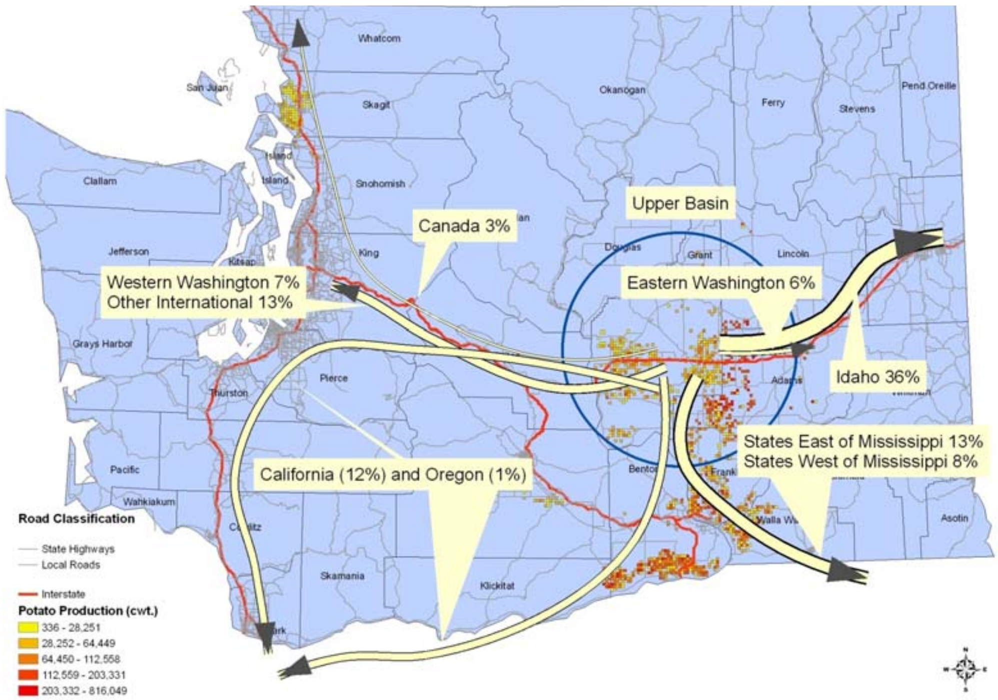


Figure 5.11 Shipment destinations for Upper Basin potato production (Creamer, Selmin and Jessup 2008)

Destinations in Eastern Washington are distributed to Moses Lake, Spokane, Kennewick, Warden, Yakima, and Grandview. Destinations in Western Washington are distributed to Seattle, Tacoma, Stanwood, and Auburn. Destinations in Oregon and California are served via I-5, I-205, I-82, and Highway 97. Destinations in Idaho are served via I-90, Highway 2, Highway 12, I-82, and I-84. Other destinations in the U.S. are served via I-90 and I-82. Destinations in Canada are served via I-5 or Highway 9. Destinations in Mexico are served via I-5, I-205, I-82, or Highway 97.

5.2.5 Truck Trips

To convert short tons to truckloads of potatoes, we assumed that fresh and dehydrated potatoes weigh out at 22,000 pounds. For frozen potatoes we assumed that a truckload can carry 20,000 pounds because of the refrigeration unit necessary. For potato chips, a truckload can carry only 5,000 pounds.

Table 5.5 Truck trips per day

Destinations		Total Production			Fresh			Frozen			Dehy			Chips		
		Skagit Valley	Upper Basin	Lower Basin	Skagit Valley	Upper Basin	Lower Basin	Skagit Valley	Upper Basin	Lower Basin	Skagit Valley	Upper Basin	Lower Basin	Skagit Valley	Upper Basin	Lower Basin
E. WA		0.17	0.06	0.12	2.90	1.71	3.96	0.00	4.17	9.67	0.00	0.24	0.53	0.00	0.27	0.63
Moses Lake	0.04	0.01	0.00	0.01	0.13	0.07	0.17	0.00	0.18	0.42	0.00	0.01	0.02	0.00	0.01	0.03
Spokane	0.48	0.08	0.03	0.06	1.40	0.83	1.92	0.00	2.02	4.68	0.00	0.12	0.26	0.00	0.13	0.30
Kennewick	0.17	0.03	0.01	0.02	0.50	0.30	0.69	0.00	0.72	1.68	0.00	0.04	0.09	0.00	0.05	0.11
Warden	0.04	0.01	0.00	0.01	0.13	0.07	0.17	0.00	0.18	0.42	0.00	0.01	0.02	0.00	0.01	0.03
Yakima	0.13	0.02	0.01	0.02	0.37	0.22	0.50	0.00	0.53	1.23	0.00	0.03	0.07	0.00	0.03	0.08
Grandview	0.13	0.02	0.01	0.02	0.37	0.22	0.50	0.00	0.53	1.23	0.00	0.03	0.07	0.00	0.03	0.08
W. WA		0.06	0.07	0.14	0.99	1.99	4.53	0.00	6.49	14.76	0.00	0.28	0.61	0.00	0.32	0.72
Seattle	0.28	0.02	0.02	0.04	0.28	0.56	1.28	0.00	1.83	4.15	0.00	0.08	0.17	0.00	0.09	0.20
Tacoma	0.23	0.01	0.02	0.03	0.23	0.47	1.06	0.00	1.52	3.46	0.00	0.07	0.14	0.00	0.07	0.17
Stanwood	0.20	0.01	0.01	0.03	0.20	0.40	0.92	0.00	1.32	2.99	0.00	0.06	0.12	0.00	0.06	0.15
Auburn	0.28	0.02	0.02	0.04	0.28	0.56	1.28	0.00	1.83	4.15	0.00	0.08	0.17	0.00	0.09	0.20
OR		0.03	0.01	0.02	0.57	0.28	0.73	0.00	0.70	1.79	0.00	0.04	0.10	0.00	0.05	0.12
via I-5	0.25	0.01	0.00	0.01	0.14	0.07	0.18	0.00	0.17	0.45	0.00	0.01	0.02	0.00	0.01	0.03
via I-205	0.25	0.01	0.00	0.01	0.14	0.07	0.18	0.00	0.17	0.45	0.00	0.01	0.02	0.00	0.01	0.03
via I-82	0.25	0.01	0.00	0.01	0.14	0.07	0.18	0.00	0.17	0.45	0.00	0.01	0.02	0.00	0.01	0.03
via Hwy 97	0.25	0.01	0.00	0.01	0.14	0.07	0.18	0.00	0.17	0.45	0.00	0.01	0.02	0.00	0.01	0.03
CA		0.35	0.12	0.15	5.81	3.42	4.63	0.00	8.34	11.29	0.00	0.48	0.62	0.00	0.54	0.73
via I-5	0.25	0.09	0.03	0.04	1.45	0.85	1.16	0.00	2.09	2.82	0.00	0.12	0.16	0.00	0.14	0.18
via I-205	0.25	0.09	0.03	0.04	1.45	0.85	1.16	0.00	2.09	2.82	0.00	0.12	0.16	0.00	0.14	0.18
via I-82	0.25	0.09	0.03	0.04	1.45	0.85	1.16	0.00	2.09	2.82	0.00	0.12	0.16	0.00	0.14	0.18
via Hwy 97	0.25	0.09	0.03	0.04	1.45	0.85	1.16	0.00	2.09	2.82	0.00	0.12	0.16	0.00	0.14	0.18
ID		0.00	0.36	0.00	0.00	10.26	0.00	0.00	25.03	0.00	0.00	1.45	0.00	0.00	1.63	0.00
via I-90	0.20	0.00	0.07	0.00	0.00	2.05	0.00	0.00	5.01	0.00	0.00	0.29	0.00	0.00	0.33	0.00

via Hwy 2	0.20	0.00	0.07	0.00	0.00	2.05	0.00	0.00	5.01	0.00	0.00	0.29	0.00	0.00	0.33	0.00
via Hwy 12	0.20	0.00	0.07	0.00	0.00	2.05	0.00	0.00	5.01	0.00	0.00	0.29	0.00	0.00	0.33	0.00
via I-82	0.20	0.00	0.07	0.00	0.00	2.05	0.00	0.00	5.01	0.00	0.00	0.29	0.00	0.00	0.33	0.00
via I-84	0.20	0.00	0.07	0.00	0.00	2.05	0.00	0.00	5.01	0.00	0.00	0.29	0.00	0.00	0.33	0.00
West of MS		0.11	0.08	0.22	1.84	2.28	6.98	0.00	5.56	17.05	0.00	0.32	0.94	0.00	0.36	1.11
via I-90	0.50	0.05	0.04	0.11	0.92	1.14	3.49	0.00	2.78	8.52	0.00	0.16	0.47	0.00	0.18	0.55
via I-82	0.50	0.05	0.04	0.11	0.92	1.14	3.49	0.00	2.78	8.52	0.00	0.16	0.47	0.00	0.18	0.55
East of MS		0.20	0.13	0.24	3.40	3.70	7.70	0.00	9.04	18.79	0.00	0.52	1.03	0.00	0.59	1.22
via I-90	0.50	0.10	0.07	0.12	1.70	1.85	3.85	0.00	4.52	9.39	0.00	0.26	0.52	0.00	0.29	0.61
via I-82	0.50	0.10	0.07	0.12	1.70	1.85	3.85	0.00	4.52	9.39	0.00	0.26	0.52	0.00	0.29	0.61
Canada		0.06	0.03	0.09	0.99	0.85	2.81	0.00	2.09	6.85	0.00	0.12	0.38	0.00	0.14	0.45
via I-5	0.50	0.03	0.02	0.04	0.50	0.43	1.40	0.00	1.04	3.43	0.00	0.06	0.19	0.00	0.07	0.22
via Sumas (Hwy 9?)	0.50	0.03	0.02	0.04	0.50	0.43	1.40	0.00	1.04	3.43	0.00	0.06	0.19	0.00	0.07	0.22
Mexico		0.02	0.00	0.00	0.28	0.00	0.04	0.00	0.00	0.11	0.00	0.00	0.01	0.00	0.00	0.01
via I-5	0.25	0.00	0.00	0.00	0.07	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
via I-205	0.25	0.00	0.00	0.00	0.07	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
via I-82	0.25	0.00	0.00	0.00	0.07	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
via Hwy 97	0.25	0.00	0.00	0.00	0.07	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Other Int'l		0.00	0.13	0.01	0.00	3.70	0.35	0.00	9.04	0.84	0.00	0.52	0.05	0.00	0.59	0.05
Port of Seattle	1.00	0.00	0.00	0.00	0.00	3.70	0.35	0.00	9.04	0.84	0.00	0.52	0.05	0.00	0.59	0.05
	TOTAL TRUCK TRIPS per DAY				16.79	28.20	31.73	0.00	70.46	81.14	0.00	3.98	4.25	0.00	4.48	5.04

Table 5.5 shows the number of truck trips per day between each origin and each destination for each product type. In all cases except for Eastern and Western Washington, we assumed that trips were equally distributed across minor destinations because of a lack of more detailed information. In Eastern and Western Washington, truck trips were distributed according to the populations of the cities identified as destinations. The minor destinations were identified in the Creamer et al. 2007 potato survey.

5.2.6 Disruption

The pattern of movements within the state clearly includes some movements of potatoes and potato products from Western Washington to Eastern Washington and vice versa. According to our estimates of truck trips, of the almost 250 truck trips generated each day in the state serving potato movements, about 50 trucks, or about 20.47 percent of all truck trips, travel over the mountain passes.

During the last ten years, heavy snow and avalanche danger have frequently caused WSDOT to close I-90 at Snoqualmie Pass. In fact, during the 2007-2008 winter season, Snoqualmie Pass was closed for roughly 370 hours (WSDOT GrayNotebook 2008a). The closures were distributed approximately equally between eastbound and westbound lanes, but eastbound traffic was slightly more affected. In the same season, Steven's Pass received 562 inches of snow. The closures of I-90 due to inclement weather also affected the other mountain routes of Highway 2 and 12. Highway 410 and Highway 20 are closed seasonally every winter, leaving SR 14, the southern-most east-west route as the only available cross-state route.

Given our decision to model this disruption to east-west routes, only a subset of the trucks needed to be re-routed (those that would normally travel the east-west routes). Truck trips that would not cross the Cascades would not be directly affected by the closure, and therefore it was not necessary to re-route them. For example, we know that shipments of fresh potatoes from Skagit County to the Port of Seattle do not utilize a mountain pass. Table 5.6 shows the routes for origins and destinations that cross the Cascades and would therefore be disrupted by a mountain pass closure. It also shows the estimated number of daily truck trips on these routes and the products they carry. Notice that I-90 carries the majority (67 percent) of the trips, followed by 410 West. Notice that the eastbound movements originate in Skagit county, which is quite far north in the state, and so eastbound movements favor the more northerly crossings, whereas the westbound movements originate farther south in the Upper and Lower basins, and so favor the more southerly routes such as 410, which only serves westbound movements.

Also notice that all of the potatoes heading east are fresh potatoes. These are potatoes grown in the Skagit Valley and transported to processing facilities on the east side of the state. However, the westbound traffic is composed of all product varieties, of which 69 percent are frozen.

Table 5.6 Truck trips per day under normal conditions on cross-Cascades routes

Normal Conditions					
	Truck Trips	Fresh	Frozen	Dehy	Chips
Hwy 2 East	4.3				
Skagit to Moses Lake		0.13			
Skagit to Spokane		1.40			
Skagit to Warden		0.13			
Skagit to other U.S. states (excluding Oregon or California)		2.62			
Hwy 2 West	1.8				
Upper Basin to Stanwood		0.40	1.32	0.06	0.06
I-90 East	1.2				
Skagit to Kennewick		0.50			
Skagit to Yakima		0.37			
Skagit to Grandview		0.37			
I-90 West	32.4				
Upper Basin to Seattle		0.56	1.83	0.08	0.09
Upper Basin to Tacoma		0.47	1.52	0.07	0.07
Upper Basin to Auburn		0.56	1.83	0.08	0.09
Upper Basin to Port of Seattle		3.70	9.04	0.52	0.59
Lower Basin to Seattle		1.28	4.15	0.17	0.20
Lower Basin to Stanwood		0.92	2.99	0.12	0.15
Lower Basin to Port of Seattle		0.35	0.84	0.05	0.05
410 West	10.6				
Lower Basin to Tacoma		1.06	3.46	0.14	0.17
Lower Basin to Auburn		1.28	4.15	0.17	0.20

The truck trips shown in Table 5.6 are represented in green on the map of Washington in Figure 5.12. Using the GIS tool, we disabled network links on I-90, Highway 2, and Highway 12 to replicate the impacts of a severe winter storm and re-routed the potato trucks to the next shortest path between their origin and destination.

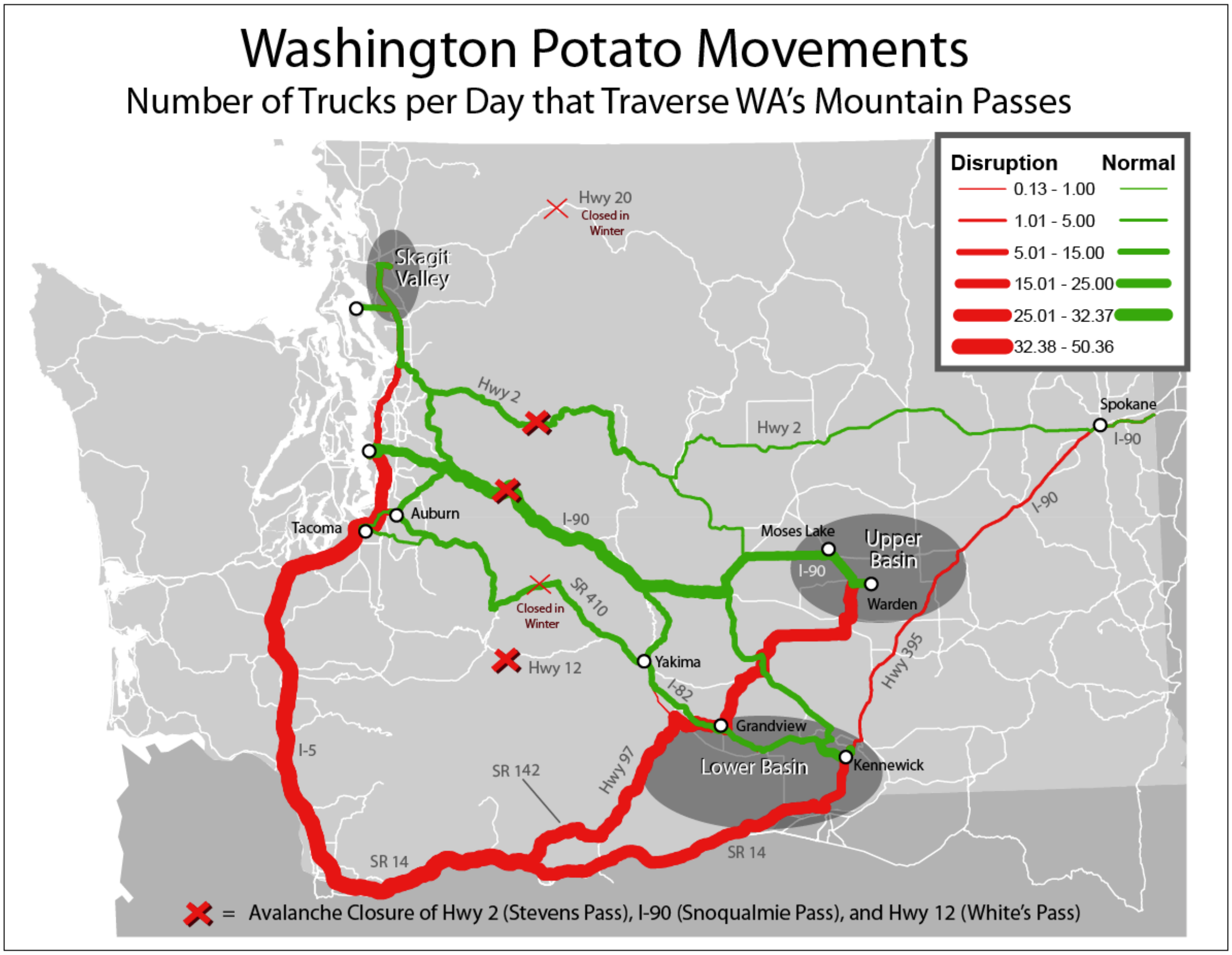


Figure 5.12 Truck trips per day on cross-Cascades routes under disruption scenario

The new routes are shown on the map in red and are further detailed in Table 5.7. We observed the rerouting to the only remaining east-west freight route, SR 14, then utilized I-5 for the north/south portion of the trip. In the base case, no trucks would use this route to cross the Cascades. The result is an increase of truck trips on these roads of about 50 trucks per day.

Table 5.7 Truck trips per day under disruption scenario on cross-Cascades routes

Disruption					
	Truck Trips	Fresh	Frozen	Dehy	Chips
I 84 East	5.5				
Skagit to Moses Lake		0.13			
Skagit to Spokane		1.40			
Skagit to Warden		0.13			
Skagit to other U.S. states (excluding Oregon or California)		2.62			
Skagit to Kennewick		0.50			
Skagit to Yakima		0.37			
Skagit to Grandview		0.37			
I 84 West	44.8				
Upper Basin to Stanwood		0.40	1.32	0.06	0.06
Upper Basin to Seattle		0.56	1.83	0.08	0.09
Upper Basin to Tacoma		0.47	1.52	0.07	0.07
Upper Basin to Auburn		0.56	1.83	0.08	0.09
Upper Basin to Port of Seattle		3.70	9.04	0.52	0.59
Lower Basin to Seattle		1.28	4.15	0.17	0.20
Lower Basin to Stanwood		0.92	2.99	0.12	0.15
Lower Basin to Port of Seattle		0.35	0.84	0.05	0.05
Lower Basin to Tacoma		1.06	3.46	0.14	0.17
Lower Basin to Auburn		1.28	4.15	0.17	0.20

The rerouting would affect about 50 truck trips per day, five in the eastbound direction and about 45 in the westbound direction, or about 20 percent of total truck trips moving potatoes in the State of Washington. Under normal conditions, trucks travel an estimated 11,000 miles each day. Under the disrupted conditions, if all trucks re-routed, truck miles would increase to almost 21,000 miles, an increase of almost 80 percent. The additional truck miles by product are shown in Table 5.8. In terms of truck miles, the greatest impact would be to frozen potatoes moving from the Upper and Lower basins to the markets on the west side of the state (including export facilities at the Port of Seattle). Fresh potatoes would also be significantly affected.

Table 5.8 Additional truck miles by product under disruption scenario

	Skagit Valley	Upper Basin	Lower Basin
Fresh	1327	1191	679
Frozen	0	3233	2170
Dehydrated	0	168	91
Chips	0	189	108

5.2.7 Economic Impacts

The economic impacts from the highway closure of I-90 described above would include a variety of both direct and indirect costs that would adversely affect the Washington state potato industry. Some of these impacts are easily identified but more difficult to measure accurately, given the dynamic nature of markets and market participants and how they respond/change in different circumstances. A discussion of these impacts, based upon the model assumptions provided above and the transportation characteristics of the potato industry collected from earlier studies, is provided below, in addition to the direct/indirect nature of how they affect the state's potato industry.

5.2.7.1 Direct Costs

The direct costs of the I-90 closure at Snoqualmie described earlier would include those additional costs associated with trucks required to travel an additional 9,148 miles (in aggregate), including added fuel consumption, truck driver wages, and vehicle operating costs. Earlier studies have estimated these costs for different commodities/general freight, which are influenced by the current price of fuel and labor market conditions, in addition to other factors that include commodity weight/density and backhaul opportunities in the geographic market served. Table 5.9 provides a list of cost coefficients from recent studies, with the truck cost per mile ranging from $1.50 to $3.50 per mile. If we apply these coefficients to the additional miles encountered from the I-90 Snoqualmie disruption, we could expect an additional $13,722 to $32,018 per day cost impact, or approximately $275 to $640 dollars per truck. This direct cost estimate range was based upon several assumptions, including the following:

- Re-routing of truck traffic as a result of an I-90 closure would occur from the shipment origin and would not account for time caught in traffic, backtracking of the route to the shipment alternative, or the cost of driver hours of service (i.e., drivers who exceeded their hours of service limits as a result of being stuck in disruption traffic would have to be replaced in order to move the shipment).

- Potato products would follow average daily historical shipping patterns, as provided by the industry, and seasonal fluctuations were ignored.
- Potato shippers would continue to ship the product when a disruption occurred, instead of delaying shipments for a period to avoid the disruption.

Table 5.9 Truck transportation cost per mile of operation for various agricultural commodities

Commodity	Cost Estimates Per Mile
Wheat, Corn and Soybeans	2.17 – 3.46
Switchgrass	1.67 – 1.87
Barley	2.30 – 3.46

5.2.7.2 Indirect Costs

The indirect costs of such a disruption would include lost market opportunities from fresh or processed potato shippers. This could be in the form of lost customers/markets as a result of shipments that failed to reach the ports of Seattle or Tacoma to meet ocean vessel shipping deadlines, thus resulting in unsatisfied customers or clients, which would adversely affect future potato sales. This would also apply to domestic retail markets in the Puget Sound area for truck shipments west of the Cascade Mountains, although for this market shippers would likely delay shipment to avoid the closure disruption. For the portion of potato shipments leaving the Skagit Valley production area and heading east to processors in the Columbia basin or markets east, the I-90 closure would also have some adverse impacts as a result of delayed delivery and/or missed market opportunities. Given the relatively small volume of shipments in this movement, the indirect impacts would likely be minor. Other indirect costs might include product spoilage/damage from shipments that were drastically delayed or diminished quality as a result of additional handling because of load transfer/reload.

Inventory costs might also increase as a result of delayed product movement, although the marginal daily cost increase is would be minor.

5.2.7.3 Discussion of Economic Implications

Figure 5.13 shows that the price of fresh potatoes is quite variable. The figure shows the average value received by the potato grower for each month over the last six years. Notice that even within one year, prices can change substantially from one month to the next.

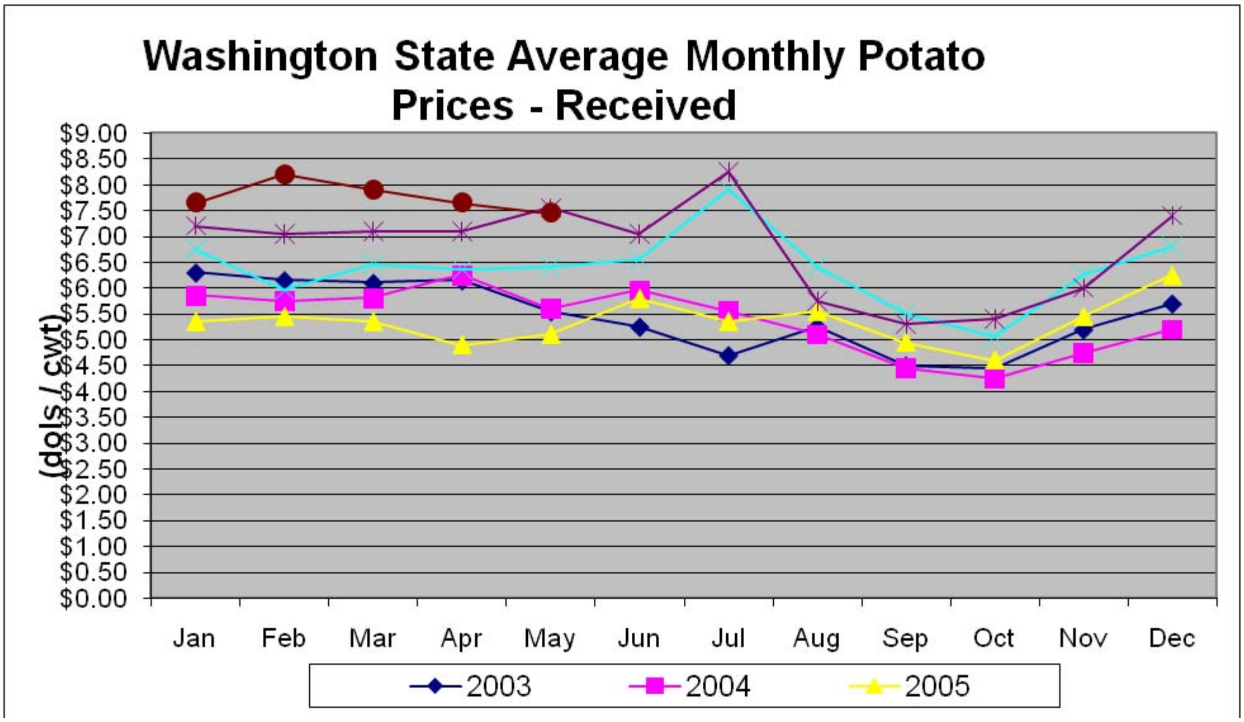


Figure 5.13 Price of fresh potatoes (source: Washington Potato Commission)

Retailers paid on average $7.83 for 50 lbs or about $15.00 per cwt, almost doubling the value from the farmer. Retailers in the Lower Yakima Valley and Columbia Basin paid almost $16.00. Potatoes from NW Washington achieved the highest price paid by the retailer, about $18.00 per 50 lbs, or $36.00 per cwt (Washington Potato Commission).

The range of prices for fresh potatoes in the store range from $.33/pound to $2/pound for organically grown, low-yield fresh potatoes. According to AC Nielsen, the average price paid for fresh potatoes in the Seattle region in 2008-2009 was $.50/pound.

Frozen French fries can be purchased for about $2/pound, dehydrated potatoes for about $2.70/pound, and potato chips range from $4.50 to $8/pound.

Given this, the value of a truckload of fresh potatoes could be as little as $1,000 with respect to the grower's revenue; however, the value of a truckload of potatoes to the grocery store is an order of magnitude larger, or about $10,000 (Table 5.10). A truckload of processed potatoes is worth substantially more, closer to $50,000 for frozen French fries, dehydrated potatoes, and about $25,000 for potato chips. These estimates are all based on the sale price of the products at the grocery store, since prices at the processing facility are not known. However, these would over-estimate the value of a truckload of potatoes.

Table 5.10 Approximate truckload value along the supply chain for each potato product

	Grower	Retailer	Consumer
Fresh	$1,000 - $5,000	$2,000 - $8,000	$7,000 - $50,000
Frozen			$40,000
Dehydrated			$60,000
Chip			$20,000-$40,000

Consider a truckload of fresh potatoes worth about $3,000. Even if a 10 percent profit could be made on this load, it would be completely offset by the cost of re-routing a truck to avoid a winter road closure. Given this, it is not surprising that many truckloads would choose to wait out the closure, rather than reroute, particularly if the length of the closure was unknown. While there are certainly quality concerns about fresh potato products, none of the experts we talked to had any concern about the effects of several days' delay on product quality.

If carriers knew at the time of the closure that the delay to the trucks would be limited to 24 hours, we can assume that a majority of potato trucks would choose not to re-route but to incur the additional cost of waiting (driver wages) for the pass to re-open. Some trucks, including those with frozen potatoes destined for the ports, might re-route if there was concern that an outbound ship would be missed. If the length of the closure were uncertain, we would see a larger volume of trucks taking the re-route. The indirect impacts, therefore, of a 24-hour closure to the potato industry in Washington state, would be minimal, although there would be significant disruption to traffic. The economic impact would be primarily the direct cost of delay to the carrier, including extra fuel, driver wages, and driver accommodations.

5.3 WASHINGTON STATE DIESEL DISTRIBUTION

This section documents the case study of diesel distribution in Washington state from the point of entry into the distribution network through the "last mile" delivery to the consumer. In addition, the vulnerability and reliability of the system when subjected to potential disruptions are discussed and evaluated for a 24-hour closure of the Washington cross-Cascades passes. With the Washington cardlock facilities as destinations and the terminal racks as origins, we mapped the roadways used to supply the cardlock facilities with fuel and thus identified the most critical routes for diesel distribution. Publicly available information as well as industry insight provided by various representatives associated with the distribution of diesel within Washington state helped us to develop the case study.

5.3.1 Fuel Distribution

The WSDOT *Washington Transportation Plan Update Freight Movement* (2008c) report contains an overview of the delivery and supply system for petroleum-based fuel in Washington state. The report summarizes the flow of refined products from the five active refineries in the state to the end user at fueling stations, Seattle-Tacoma International Airport (Sea-Tac), the maritime industry, and for home heating. The three modes of transportation for movements within the supply system are pipeline, marine vessels (tanker or barge), and truck. The report also briefly discusses issues of concern within the fuel distribution system, including capacity constraints at the refineries, storage facilities, and on the pipelines; safety considerations; and price and demand volatility due to the economic proximity of the Washington state industry to the whole of the West Coast.

A report prepared by ICF International for the State of Washington Energy Facility Site Evaluation Council (2007) describes factors that contribute to high diesel (and other fuels) prices and increased price volatility in southwest Washington and northwest Oregon. In addition to addressing pricing and supply and demand patterns, the report describes the infrastructure of the diesel distribution system within Washington state. The report identifies the Portland/Vancouver area as being the hub of the distribution network in the Northwest, as it receives and distributes product via pipeline, marine vessel, and tanker truck. It also states that price volatility is likely to be persistent in the coming years, as potential supply shortages are susceptible to propagation, with higher demand being placed on the infrastructure network.

- The term "product" refers to an aggregate sum of diesel, gasoline, jet fuel, or potential other petroleum products because information is not available on the disaggregated diesel level.
- The diesel transportation/distribution network in Washington state may be referred to as two distinct sections: the Upper Distribution Network (UDN) and the road network. The UDN refers to a combination of the pipeline network and the waterway network that transports diesel product from refineries to the terminal locations where the road network system begins. The road network interfaces with the UDN at terminals and contains the roadways, the tanker trucks, and the final destination locations of the total diesel distribution network. Tanker trucks complete the "last mile" delivery of the distribution network to the consumer.
- A terminal is located at the end of a pipeline or at a port where waterborne vessels offload transported diesel product from a refinery. Tanker trucks that complete the "last mile" delivery of the distribution network load diesel product at terminals and transport it to cardlock locations such as those contained in the Commercial Fueling Network (CFN) or Pacific Pride diesel fueling network.
- Cardlock facilities are diesel distribution locations which are unstaffed. Diesel can be purchased with a previously obtained card. Due to the reduced

management cost, these are common facilities used in diesel distribution. This study only mapped cardlock facilities, not all diesel distribution stations.

5.3.2. Methodology

5.3.2.1 Research Design

This case study began with a comprehensive exploration of the Washington state diesel distribution system. The data collection and information gathering were completed by investigating publicly available information from numerous governmental agencies and inquiring with private entities that operate within the diesel distribution network. The intent was to build an understanding of the flow of diesel from points of entry to points of consumption. This included the infrastructure and modes of transportation that facilitate distribution; the locations and operations of refineries, terminals, and destinations; and the volumes of flow between these locations. Collection of the physical features of the network allowed for construction of the network within the statewide freight model, and collection of flow data allowed for a macro-level understanding of where and how diesel is distributed throughout the state.

5.3.2.2 Data Gathering

Information describing the diesel distribution network within Washington state is not readily available and is held in a multitude of locations by a number of agencies. Each agency holds this information for its own reasons. Data collection mechanisms vary, as do levels of spatial and temporal resolution and data quality. The researchers made inquiries to state and federal agencies, reviewed commodity flow and statistical databases, interviewed representatives of the transportation and purchasing elements within the system, and reviewed official reports. The following paragraphs describe the locations and sources of investigation, the effort required, and the information obtained from each inquiry.

- The initial effort involved exploring existing documentation that describes the diesel distribution system in Washington state. Two reports containing the physical structure and important elements of the network were reviewed, and pertinent information was extracted for further investigation. The WSDOT

Washington Transportation Plan Update Freight Movement (2008c) provides general information on the locations of refineries, pipelines, and terminals, and outlines the distribution of petroleum products on an aggregated level within Washington state and to other locations. The State of Washington Energy Facility Site Evaluation Council report completed by ICF International (2007) verifies much of the information provided in the WSDOT report while also describing in greater detail the pipeline and barge movement operations along the supply chain. A review of the *Washington State Freight and Goods Transportation System (FGTS) 2007 Update* (2008b) provided an understanding of the roadway network within the state as it applies to the movement of freight.

With a general understanding of the infrastructure and operations involved to move petroleum products within the Washington state distribution network, the next step involved isolating portions of the system that distribute diesel product and searching for specific flow and origin-destination data.

- The Washington State Department of Agriculture (DOA*)* regulates the accuracy of the quantity and quality of fuel delivered at gas stations in the state. The locations that it monitors are based on a list of businesses that have fuel meters registered with the Washington State Department of Licensing (DOL). Contact was made with the DOA through its website, and a database containing the locations of fuel meters was obtained. However, the list only separated locations by geography, not by fuel type.
- The Washington State Department of Ecology (ECY) regulates active underground storage tanks (USTs) in the state. The agency is responsible for ensuring that tanks are installed, monitored, and managed in order to prevent hazardous material releases into the environment. Contacts were made within the ECY through the Governor's Office of Regulatory Assistance to obtain a database containing all active USTs. The database contained 2005 data for tank volume, fuel type, geographic coordinates, and physical addresses for 10,869 USTs, of which 2,378 were classified as holding diesel fuel. Although current information for each tank could be queried by a variety of selection

options at the following ECY Web portal (https://fortress.wa.gov/ecy/tcpweb reporting/reports.aspx), the information was provided only in summary. The database acquired directly from ECY personnel was in an easy to sort Microsoft Excel spreadsheet containing all locations in list format. The ECY personnel verified that the data provided in the 2005 database were substantively comparable to the current year database and that the current year database was not available in a format that could be as easily extracted as the 2005 database.

- Similarly, the Environmental Protection Agency (EPA) regulates above-ground storage tanks (ASTs). An AST is defined as a tank that has more than 90 percent of its storage capacity above ground. A contact for the EPA was obtained from the ECY, and a database containing all current year ASTs was acquired. Although we were less certain as to the specific formulation of the database in comparison to the USTs database, the ASTs database contained tank volumes, fuel types, and physical addresses for 67 identified tanks containing diesel.
- The Washington State Department of Revenue (DOR) is responsible for assessing and collecting fuel taxes at terminal locations throughout Washington state. The tax is applied per gallon of fuel that is distributed from the terminal locations. Using their database, the DOR provided a list of active terminal locations in Washington state. There were 27 terminal locations, including the five refineries.

The collection of the above information provided detailed information on the locations of origins and destinations within the diesel distribution network of Washington state. Figure 5.14 shows the locations of the 27 terminal racks in the state. An additional exercise consisted of matching UST and AST locations and volumes to the complete list of cardlock locations of the Commercial Fueling Network (CFN) and Pacific Pride diesel fueling network. Actual cardlock locations were obtained from each company's website (http://www.cfnnet.com/ and http://www.pacificpride.com/) and matched with the locations of USTs and ASTs. In total, 376 of 433 (86.8 percent) cardlock locations were matched with actual diesel tank locations. This dataset provided a reliable group of known diesel distribution destination locations with tank volume data, and these were specifically loaded into the statewide freight tool.

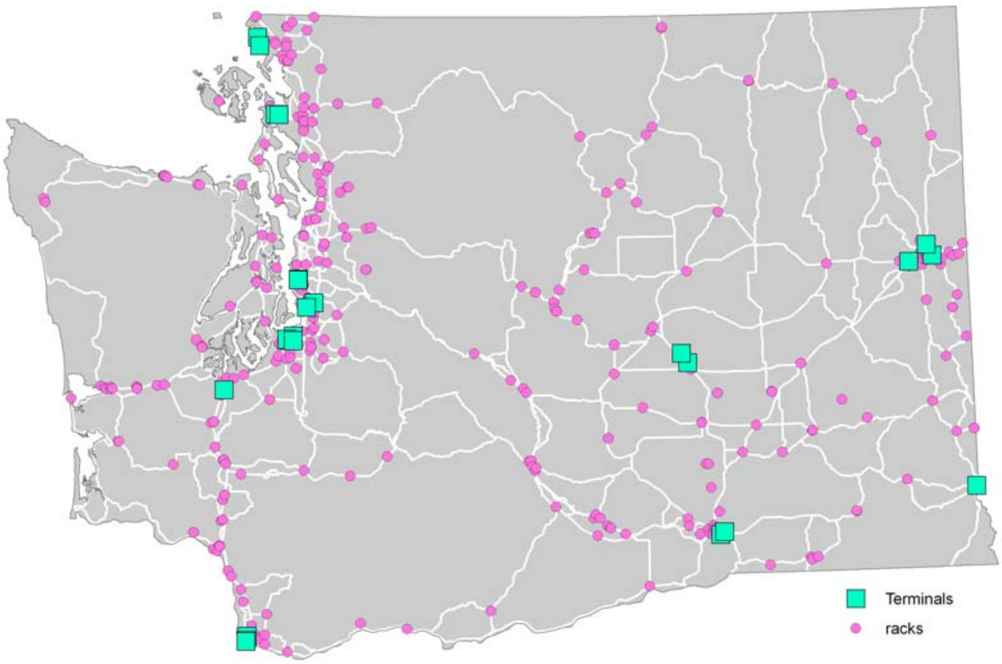


Figure 5.14 Diesel terminal and cardlock (rack) facilities in Washington state

Data regarding fixed infrastructure and capacity, while somewhat time consuming to track down, were readily available in comparison to data on movements. Data on movements were inherently more difficult to obtain, as they vary quickly over time, and space. Fixed infrastructure, on the other hand, changes much more slowly.

5.3.2.3 Waterway Movement

- ECY publishes the annual *Vessel Entry and Transit for Washington Waters (VEAT)* report that identifies vessels in Washington state waters tracked by the ECY (http://www.ecy.wa.gov/programs/spills/publications/publications.htm).

Although the report tracks tanker ships and barges transporting oil, it only provides a count of vessels; it does not specify the origin, is not destination specific, and is not disaggregated for diesel product.

- Another contact was made for the ECY through the Governor's Office of Regulatory Assistance. Through the Advanced Notice of Oil Transfer (ANT) program (http://www.ecy.wa.gov/programs/spills/prevention/antsystem.html) ECY tracks all waterborne movements of oil products in Washington state that are greater than 100 gallons and that are going to be delivered to a non-recreational vessel or facility. These data are disaggregated by outbound and inbound traffic; however, the outbound data included only exports, and the inbound data were not origin specific. A year's worth of data for fiscal year 2008 was obtained, including volumes of diesel transported.
- The Pacific Merchant Shipping Association and the Maritime Administration (MARAD) were contacted, but both groups stated that they do not track waterborne origin-destination fuel movement.
- *The Destination and Origin of Waterborne Commerce of the United States, 2007* report from The Waterborne Commerce Statistics Center of the Army Corps of Engineers Institute for Water Resources (2008) (http://www.ndc.iwr.usace.army.mil/wcsc/wcsc.htm) contains aggregated petroleum and crude waterborne imported and exported data for Washington state, but they are not disaggregated for diesel product and are only origin-destination specific by state or country.

5.3.2.4 Pipeline Movement and Refinery Capacity

- The researchers contacted ConocoPhillips Pipeline (owner of the Yellowstone Pipeline), Chevron Pipeline Company (owner of the Chevron Pipeline), and Kinder Morgan (owner of multiple terminals in Washington state) but each declined to participate in the research.
- The Energy Information Administration (EIA) maintains State Energy Profiles that contain a compilation of various aggregated fuel production and consumption data by state; the *Washington State Energy Profile* was obtained

from the EIA website (http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=WA). The EIA also publishes the *Refining Capacity Report* (2008) (http://www.eia.doe.gov/oil_gas/petroleum/data_publications/refinery_capacity_data/refcapacity.html), which reports the total production capacity at each Washington state refinery. Although the EIA does not disaggregate production of diesel at each refinery because of confidentiality issues, an EIA official provided an estimate of 20 percent diesel production for total Washington state refined production.

- Form 6-Annual Report of Oil Pipeline Companies is a form that the Office of External Affairs (OEA) of the Federal Energy Regulatory Commission (FERC) requires each pipeline company to annually submit to report financial and operational information. Filed Form 6's are available at http://www.ferc.gov/docs-filing/eforms.asp#6. The submitted 2007 Form 6's were obtained for the Olympic Pipeline, the Yellowstone Pipeline, the Chevron Pipeline, and the Trans Mountain Pipeline. These forms disaggregate pipeline flow for product type by "Originated On" and "Terminated On" the respective pipeline.
- The Western States Petroleum Association and the Washington Research Council collaborated on a report entitled *The Economic Contribution of Washington State's Petroleum Refining Industry in 2005*. The report mostly pulls data from the EIA and a refinery survey to summarize Washington state refining capacity by product, mode of transportation for distribution, and aggregated destination locations.

5.3.2.5 Roadway Movement

- The Strategic Freight Transportation Analysis (SFTA) at Washington State University conducted a roadside origin-destination survey of freight trucks in 2003 and 2004. The database is categorized by UN placard number (1202 and 1203 for petroleum products), payload weight, and origin-destination (city, state) for the surveyed truck trips. Although this database contains empirical trip counts with pertinent associated data, the trip counts for petroleum products are quite low, the type of petroleum product being moved is undefined, and expanding the trips to incorporate the entire state or a section of the state is unreliable because of uncertainties in how the survey was conducted.

- The Freight Analysis Framework (FAF2) is an origin-destination database published by the Federal Highway Administration (FHWA) based on data collected during the 2002 Commodity Flow Survey. Report Number S6 – Petroleum National Totals (http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_tech_document.htm) provides national aggregated movement totals for petroleum products by pipeline, water, highway, and rail. The information provided in the FAF2 is unusable because the report does not have specific data for Washington state, and there are reported inconsistencies in the collected totals.
- Both the Washington State Utilities and Transportation Commission and the Washington State Office of Financial Management were contacted, but they did not posses any pertinent information.
- The Washington Oil Marketers Association provided a significant amount of information describing the Washington state diesel distribution network. It made note of the relationship between the marketers and the major oil companies and verified the general diesel supply chain network. It also provided names and contacts for diesel distribution marketers.
- Eight marketers were contacted with questions about the distribution of diesel by their companies. Three companies responded and provided valuable information that connected many of the missing pieces of the Washington state diesel distribution network not previously uncovered by the research.
- The Federal Motor Carrier Safety Administration (FMCSA) was contacted to obtain information about the reporting requirements of the diesel distributors/marketers. According to federal regulations, a carrier is required to have a HAZMAT safety permit issued by the FMCSA and a Certificate of Registration issued by the Pipeline and Hazardous Materials Safety Administration (PHMSA) to conduct diesel delivery operations (these last for

several years). The carrier is only required to report an individual movement in the case of a hazardous material spill.

5.3.3 Summary and Limitations of Data

After an exhaustive search for existing data, including requests to specific fuel marketers, we remained unsuccessful in obtaining roadway flow data for diesel. We were, however, successful in developing a thorough understanding of the infrastructure, mode choices, and *general* flow patterns and volumes. The actors that participate in the supply chain incorporate a three-tier structure of major oil companies, marketers, and cardlock locations or other consumers (Figure 5.15).

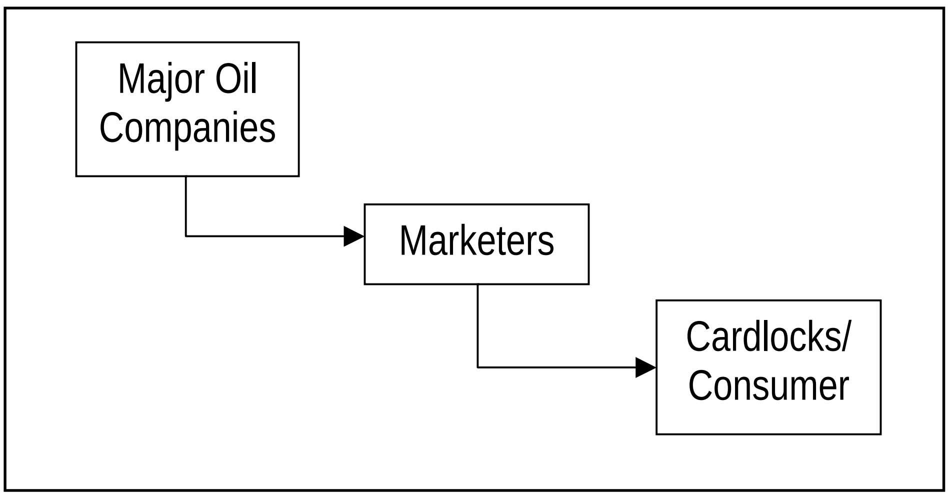


Figure 5.15. Diesel supply system actors

The major oil companies (BP, Shell, ConocoPhillips, U.S. Oil, and Chevron[7] – defined by ownership of their own crude oil reserves) refine crude oil into diesel and transport their product by way of pipeline, marine vessel, or tanker truck. (Tesoro produces diesel as well but was not considered a major oil company because it purchases crude oil from the major oil companies rather than sourcing it itself.) The pipelines are each owned and operated by one of the major oil companies (Olympic Pipeline – BP, Yellowstone Pipeline – ConocoPhillips, and Chevron Pipeline – Chevron). Independent

[7] Although Chevron does not operate a refinery in Washington state, it imports diesel into the state via the Chevron Pipeline from Utah.

operators in the marine industry contract with the major oil companies to move diesel by barge or tanker ship, and the tanker trucks are operated by independent companies known as marketers. Diesel that is transported by a pipeline or marine vessel is offloaded at one of the 27 terminal locations in the state. The terminals owned and operated by a major oil company are known as proprietary terminals, and those owned and operated by an independent terminal operator are known as common terminals. For instance, BP and Shell have terminals in Seattle on Harbor Island, and ConocoPhillips has terminals in Renton and Tacoma. Common terminals are owned by NuStar in Tacoma and by Kinder Morgan on Harbor Island. From the terminals, a marketer purchases diesel and makes delivery to a cardlock location, other fueling stations, directly to fleets of vehicles, or as specified by its customers. In addition, the major oil companies can contract directly with the marketers to transport diesel directly from a refinery.

Data are only as accurate as the source that collects and keeps them. Most of the collected information came directly or indirectly from public agencies, and we made the assumption that, as public entities, they have an interest in maintaining accurate records.

In addition, when the researchers contacted each source, they thoroughly described the intent of the project. In each instance of a willing participant, the individual providing the feedback was believed to be acting in good faith and providing information as accurately as possible.

Although statistics for the flow of diesel in the pipelines and by marine vessel were obtained, a complete picture of the flow of diesel product in Washington state was not achieved. Transportation of diesel through pipelines and via the waterways is required by federal law to be reported. However, the “last mile” delivery portion of the diesel distribution network is operated by independent marketers. Although the marketers have a respectful working relationship among themselves, the industry is highly competitive. Each marketer operates in a proprietary manner and is not required to report the volume of its movements unless a HAZMAT spill occurs. As a result, the “last mile” flow data are not publicly available and are not accessible directly from the marketers. In fact, marketers were contacted individually and asked to share data regarding the volumes of diesel they distributed, but all declined.

5.3.4. Findings

5.3.4.1 Description of the Diesel Distribution Network in Washington State

The movement of diesel in Washington state involves a multi-modal system of pipelines, waterborne vessels (barge and tanker), and tanker trucks that make the "last mile" delivery of diesel product to the consumer. The supply chain begins at the source, whether in northern Alaska where crude oil is pumped to Valdez, Alaska, and loaded onto tanker ships to be transported to Washington state, or imported from oil fields in Alberta or British Columbia, Canada, via the Trans Mountain Pipeline, or transported by oil tanker from another foreign source. In 2007, 210.5-million barrels (1 barrel = 42 gallons) of crude oil entered Washington state via tanker ships and the Trans Mountain Pipeline. Table 5.11 summarizes imported crude oil for 2007.

Table 5.11 2007 Crude imports by mode and origin (barrels/year)

	Alaska	Canada	Foreign	Total
Tanker Ship	134,622,054	1,261,543	35,294,454	171,178,050
Pipeline	39,352,689	-	-	39,352,689
	173,974,743	1,261,543	35,294,454	210,530,739

Source: 2007 Form 6 for Trans Mountain Pipeline and Destination and Origin of Waterborne Commerce of the United States, 2007

Five refineries in Washington state receive crude oil and have a total refining capacity of 627,850 barrels per calendar day of petroleum product, or 229.2 million barrels per year EIA 2008. Given the 2007 imported crude value stated above, the five refineries operate at approximately 92 percent of their capacity. Approximately 20 percent (42.2 million barrels) of the refined capacity are dedicated to producing diesel product[8]. This is equivalent to 270 gallons of diesel per year for each man, woman, and child in Washington state[9]. Refined product is transported to terminals in Puget Sound from the refineries in northwest Washington and along the Columbia and Snake rivers via the Olympic Pipeline and waterborne vessels. In addition, the Yellowstone Pipeline pumps refined product from Montana, and the Chevron Pipeline moves petroleum

[8] Estimated by an EIA official
[9] Washington state population is 6,549,224, reported by the U.S. Census Bureau for 2008: http://www.census.gov/

product from sources in Utah. The "last mile" of the diesel distribution network involves tanker trucks loading product at terminals and making deliveries to fueling stations and other customers on a daily basis. Figure 5.16 summarizes flow within the Washington state diesel distribution network.

5.3.4.2 Refineries

Four of the five refiners are located in northwest Washington and receive crude oil via tanker ship and the Trans Mountain Pipeline that crosses into Washington from Canada. The fifth is located in Tacoma; it only receives crude oil via tanker ship, as it is not connected to a pipeline terminal. Table 5.12 summarizes refinery capacity in Washington state by total petroleum product and diesel product. Figure 5.17 presents a map showing the locations of the refineries.

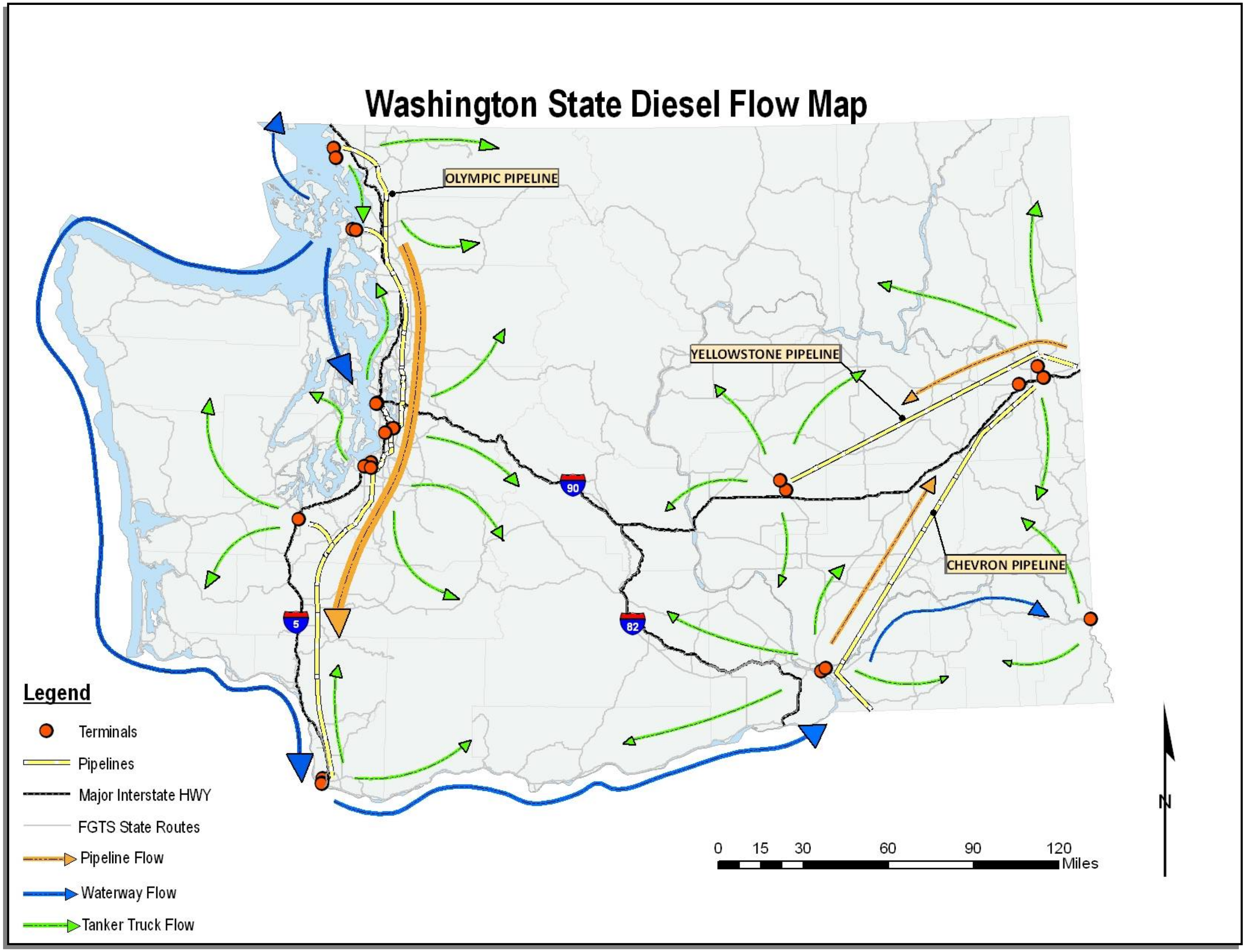


Figure 5.16 Washington state diesel flow

Table 5.12 Refinery capacity (barrels/calendar day)

Refinery	Location	Total Capacity	Percent Diesel
BP West Coast Products LLC	Ferndale	225,000	20%
CononcoPhillips Company	Ferndale	100,000	20%
Shell Oil Products US	Anacortes	145,000	20%
Tesoro West Coast	Anacortes	120,000	20%
US Oil & Refining Co.	Tacoma	37,850	20%
	Total	627,850	125,570 *

* The EIA does not disaggregate diesel production per refinery because of confidentiality issues. 125,570-barrels/calendar day is the estimated production capacity of diesel, based on an estimated 20 percent diesel production capacity for Washington state obtained from an EIA official.

Source: 2008 EIA Refinery Capacity Report

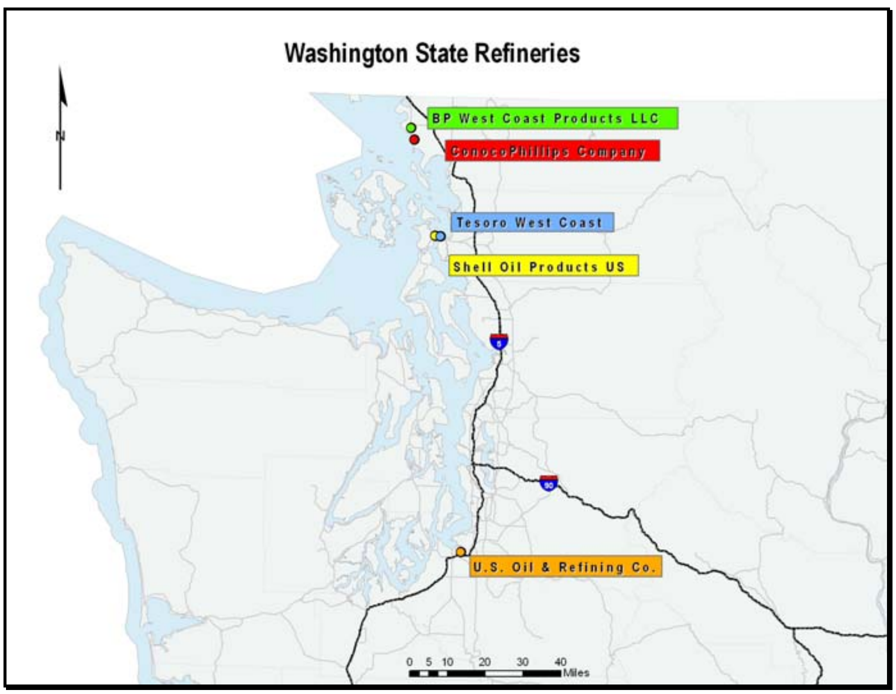


Figure 5.17 Washington state refinery locations

From the refineries, diesel is further transported along the diesel supply chain by one of three ways: pipeline, waterway, or tanker truck. A Washington Research Council Report (2007) stated that in 2005, 53 percent of diesel product refined in Washington state was shipped by pipeline, 38 percent shipped by waterway, and the remaining 9 percent was transported by other modes (presumably by tanker truck to destinations near the refineries). Table 5.13 summarizes the mode split of petroleum and diesel product transported from Washington state refineries in 2005.

Table 5.13 2005 Transportation mode split from Washington state refineries (%)

	Pipeline	Waterborne	Other
Total Petroleum Products	52	36	12
Diesel Products	53	38	9

Source: Washington Research Council (2007)

This same report states that 60 percent of refined diesel in Washington state has an in-state destination, while 40 percent is transported to other states (mostly Oregon and California), and less than 1 percent is sent to foreign locations.

5.3.4.3 Pipelines

The majority of refined diesel in Washington state is transported from the refineries to terminal locations via pipeline. Three principal distribution pipelines in Washington state transport diesel: Olympic Pipeline, Yellowstone Pipeline, and Chevron Pipeline.

The Olympic Pipeline stretches the length of the western side of the state, from Ferndale at the BP West and ConocoPhillips refineries, and from Anacortes at the Shell and Tesoro refineries, to terminal locations in the Puget Sound area, Tacoma, Olympia, Vancouver, Washington, and Portland, Oregon. The pipeline system runs 400 miles with pipe sections of 9 in., 12 in., 14 in., 16 in., and 20 in.[10]. In 2007 the Olympic Pipeline Company reported that it transported 104.4 million barrels of petroleum product, of which 28 percent was diesel[11]. The pipeline has been operating near capacity for many years and has not been expanded since it was completed in 1971.

The Yellowstone Pipeline was built in 1953, originates in Billings, Montana, and services Spokane and Moses Lake. The 10-inch pipeline owned by ConocoPhillips runs

[10] Retrieved from the Olympic Pipeline Company website: http://www.olympicpipeline.com/index.html
[11] Retrieved from the FERC Form 6 for the Olympic Pipeline Company for the reporting period ending in 2007/Q4

654 miles[12] and in 2007 transported 5.6 million barrels of petroleum product into Eastern Washington, of which 19 percent was diesel[13].

The Chevron Pipeline was built in 1950 and runs from Salt Lake City, Utah, into Pasco and Spokane. In 2007 it reported pumping 5.3 million barrels of petroleum product into eastern Washington, 27 percent being diesel[14]. Figure 5.18 shows the locations of the three principal pipelines in the state.

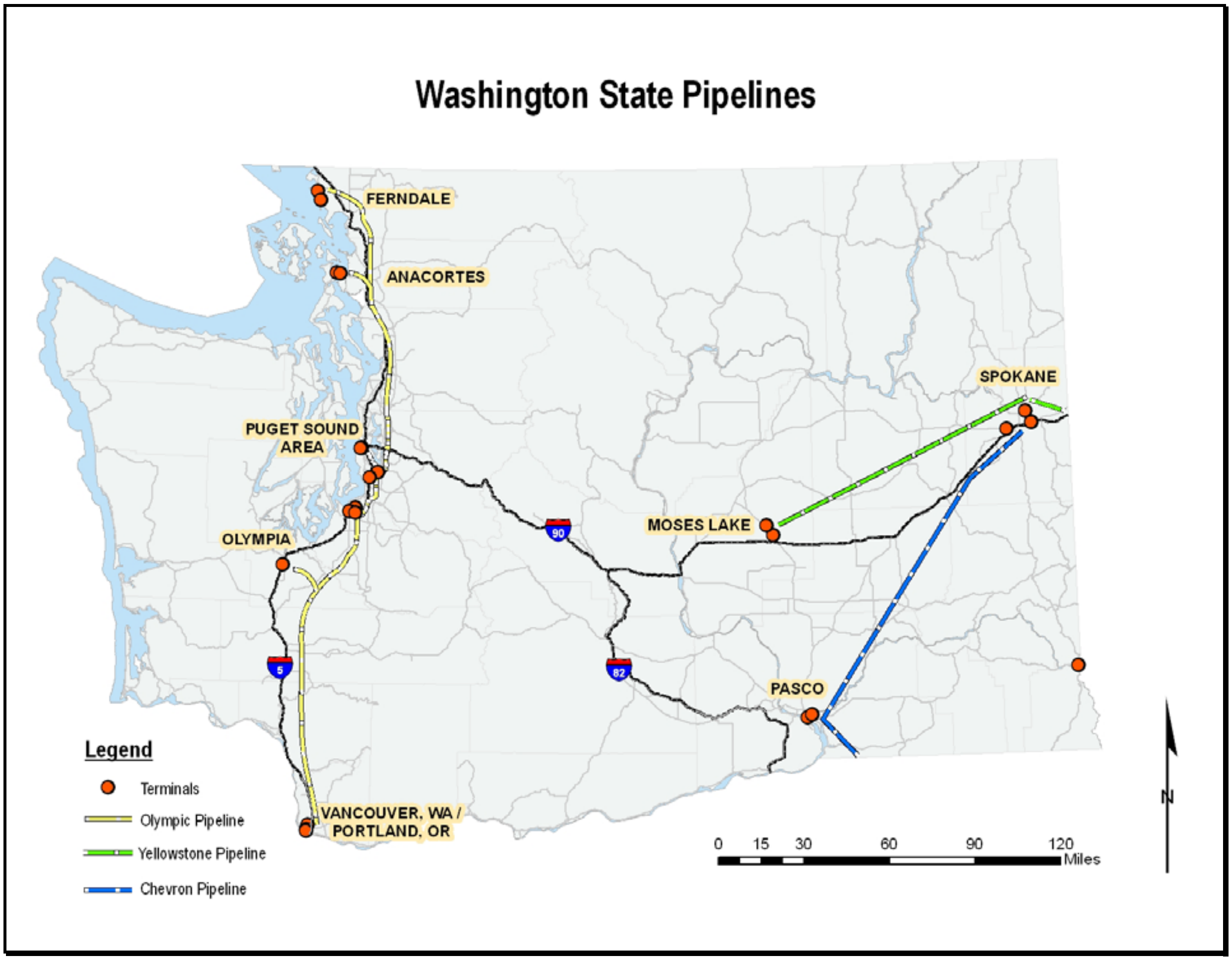


Figure 5.18 Washington state pipelines that transport diesel

[12] Retrieved from the ConocoPhillips websites: http://www.conocophillips.com/index.html

[13] Retrieved from the FERC Form 6 for the Yellowstone Pipe Line Company for the reporting period ending in 2007/Q4

[14] Retrieved from the FERC Form 6 for the Chevron Pipe Line Company for the reporting period ending in 2007/Q4

Pipeline is the most efficient and economic mode of moving diesel in Washington state. It provides the lowest shipping rate and is the most reliable origin to destination carrier of the three modes. For instance, the Washington State Plan Update Freight Movement (WSDOT 2008c) reports that one barrel of fuel moved between Ferndale and Tacoma on the Olympic Pipeline costs 1.0 cent in comparison to 1.8-cents by barge.

The operations of a pipeline involve shipping batches of distinct product in sequence to avoid contamination of one product by another. The products are injected into the pipeline one after the other based on the basis of the oil company's required batch sizes. Diesel is shipped on the basis of a schedule set by the major oil company at the head of the pipeline, but it can also operate in a fungible mode, meaning that diesel product meeting the same grade and specifications of multiple oil companies may be mixed in a single batch and transported to a common terminal, where it is sold from a single inventory. However, when diesel product is transported to a proprietary terminal, the diesel is offloaded from the pipeline to the terminal company that shipped the specific batch.

The Olympic Pipeline operates 24 hours a day, seven days a week, yet demand on the pipeline from shippers usually exceeds capacity. As the transport speed within a pipeline is not very fast (3 to 8 miles per hour), it can take 24 to 48 hours for a batch of diesel to reach its terminal destination (depending on the locations of the origin and destination). The Olympic Pipeline has a capacity of about 300,000 barrels of petroleum product per day, but numerous variables affect the attainment of this volume. First, the pipeline requires annual maintenance in order to prolong its operational life. In addition, emergency repairs can be required without notice, causing portions of the pipeline to be shut down for a period of time. These shut-downs are usually not longer than one or two weeks, and the capacity upstream of the repair/maintenance location remains active, but these events cause disruptions in the supply chain. Similarly, each refinery is required to shut down for annual maintenance every year, thus reducing the source of flow in the pipeline. The refineries are usually able to plan together so as not to cause sustained supply disruptions, but there can be times when the refineries are unable to meet the required shipping schedule as a result of operational constraints or reductions in crude oil supply. There have also been extended outages of segments of the pipeline due to unplanned fuel leaks.

All things being equal, shipping diesel by pipeline is the preferred mode of transport in Washington state. The oil companies base their transportation decisions primarily on cost; this favors pipelines in comparison to either barge or tanker truck. The Olympic Pipeline has the advantage of economies of scale over truck transportation because more product can be shipped over a longer distance. For example, it would take 53 10,000-gallon tanker trucks per hour to move the same 300,000 barrels per day that the Olympic Pipeline is able to transport. In addition, although pipeline and waterborne movements share the advantage of economies of scale, pipeline is still cheaper and more reliable because waterborne movements are susceptible to weather delays and price fluctuations caused by variability in the price of oil.

5.3.4.4 Waterways

The second most common and economical mode of transport for long haul shipments of diesel in Washington state is via waterways (short sea shipping). According to the Washington Research Council (2007), in 2005, 38 percent of diesel product refined in Washington State was transported from the refineries via waterborne vessels. These movements are primarily from the four refineries in the northwest portion of the state into the Puget Sound, Alaska, California, Oregon, or Canada, or from the Vancouver, Washington, or Portland, Oregon, terminals up the Columbia River to Pasco or Clarkston, Washington, or Umatilla, Oregon. Although tanker ships can be used, the majority of waterborne diesel movements are by way of barge. Like pipelines, barges take advantage of economies of scale on the basis of the volume that can be shipped during a single movement. The largest barges that move up the Columbia River are able to transport 1.7 million gallons of diesel to Pasco. According to a report prepared by ICF International for the State of Washington Energy Facility Site Evaluation Council (2007), marine shipments are typically more expensive then movements via the Olympic Pipeline, but only by a few cents per gallon. Without weather disruptions, a barge shipment from one of the four refineries into the mouth of the Columbia River takes typically about 36 to 42 hours (ICF 2007).

Figure 5.19 shows the waterborne diesel movements in the state, while Table 5.14 summarizes the number of vessels and volume of diesel transported by waterway. Diesel represents approximately 18 percent of all refined petroleum waterborne product movements in Washington state.

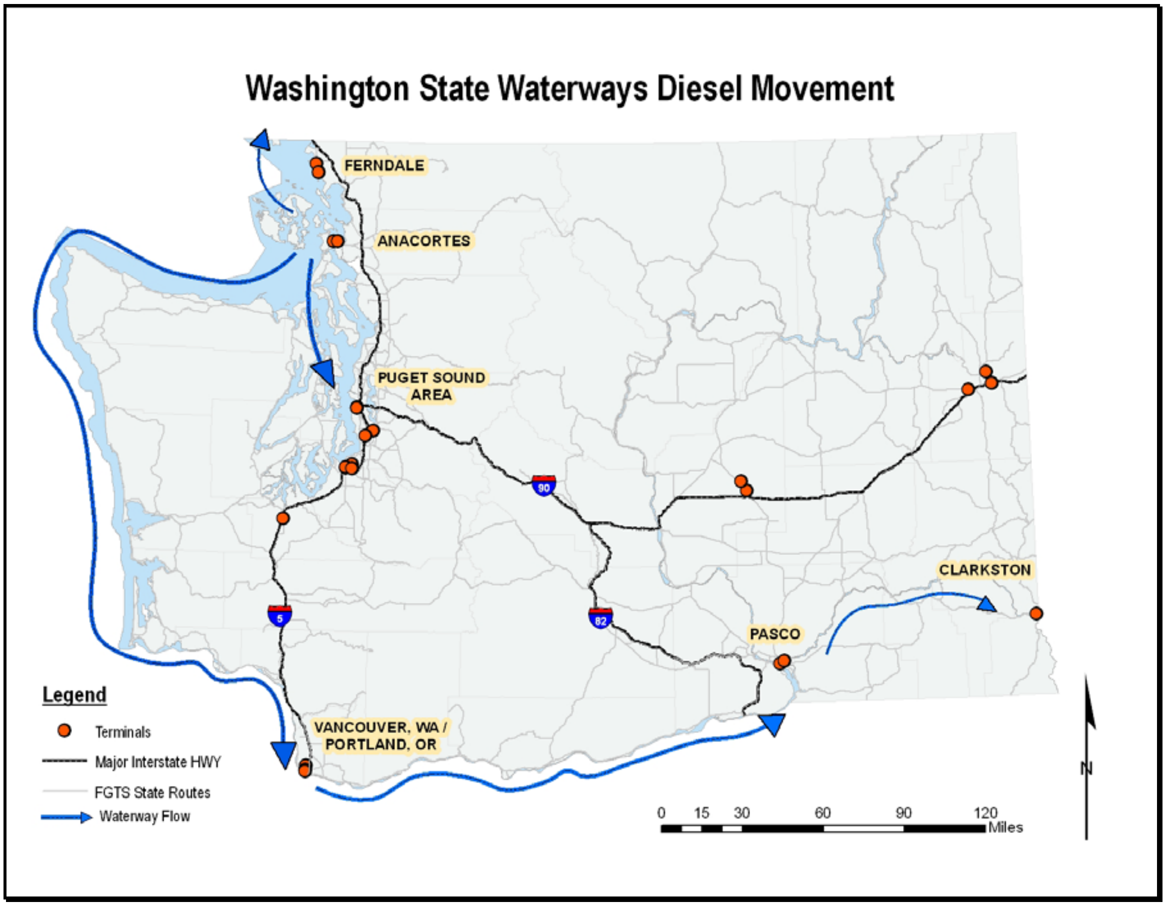


Figure 5.19 Washington state waterway flow of diesel

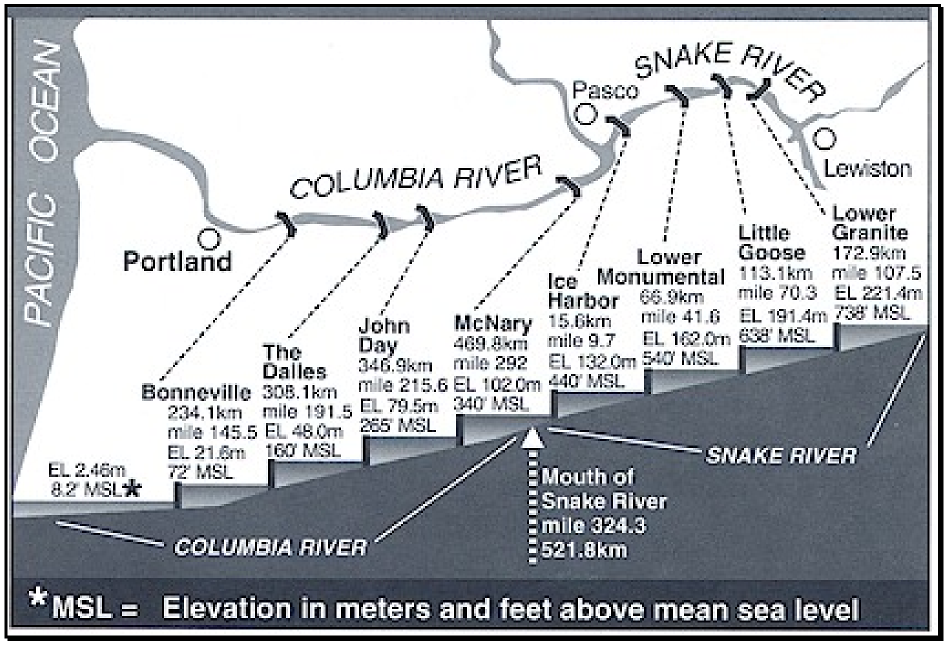
Table 5.14 2008 Washington state waterborne diesel movement by destination

	Puget Sound	Mouth of Columbia River*	Upper Columbia River**	Other***	Total
Volume (Gallons)	131,775,848	4,116,000	301,794,097	325,962,000	763,647,945
Vessels	139	5	334	68	546

* Includes Vancouver, Wash. & Portland, Ore.
** Includes Pasco, Clarkston, Wash., and Umatilla, Ore.
*** Includes Alaska, Canada, California, Oregon, and other foreign loc ations
Source: Data summarized from the Washington state Department of Ecology's Advanced Notice of Oil Transfer 2008 database.

In comparison to the volume of diesel supplied by the Chevron Pipeline and the Yellowstone Pipeline, eastern Washington depends on marine transport via the Columbia River for nearly 87 percent of its consumed diesel. According to the ICF International (2007) report and the *Washington State Plan Update Freight Movement* (WSDOT 2008) manual, there is excess capacity in the marine industry. However, this may change in the coming years as the requirement for double-hull vessels becomes the industry standard.

Barge movements are susceptible to two major common disruptions that can cause temporary supply shortages at marine terminals: weather and lock maintenance. Severe weather at the mouth of the Columbia River or anywhere along the marine route can cause delays that result in deliveries being several days late. These unplanned disruptions can cause significant supply issues if the expecting terminal is unable to source diesel from a different mode of transportation. The extensive locks system along the Columbia and Snake rivers contains eight operational locks that allow vessels to move all the way up the river to Clarkston (near Lewiston). See Figure 5.20 for a profile view of the Columbia and Snake rivers locks. Although the locks enable upriver movement, they prevent marine transport when they are shut down for maintenance. These events are usually planned and thus terminal operators and marine transporters can strategically plan to absorb the shut down time.



Source: http://w3.gorge.net/casiera/columbia.htm#locks

Figure 5.20. Columbia and Snake rivers locks

A current project on the lower Columbia River will deepen the navigation channel to ensure that the river will continue to be an operational thoroughfare for larger and more efficient maritime vessels[15].

However, there are current plans to build a petroleum pipeline from Utah to Las Vegas, Nevada. The completion of this project will place additional constraints on the quantity of diesel product available to ship into eastern Washington via the Chevron Pipeline and will certainly place more demand on the waterway transport industry to complete diesel deliveries to Pasco and Clarkston.

5.3.4.5 Tanker Trucks

The "last mile" segment of the diesel delivery network in Washington state is a 24-hour-per-day, seven-day-per-week operation completed by tanker trucks. Transportation of diesel by tanker truck is by far the most expensive mode in comparison to pipeline and marine vessel, but it is essential because of the roadway infrastructure

[15] Retrieved from the Pacific Northwest Waterways Association Website (PNWA): http://www.pnwa.net/new/

necessary to complete the final leg of the distribution network. Tanker trucks are owned and operated by marketers that purchase diesel from the major oil companies at terminal locations and transport the product to the consumer. This is different from carriers in many other industries, who do not own the product and cannot profit from price differences between the time of pick-up and delivery. Some marketers operate their own cardlock locations, but they also deliver to other independent cardlock locations, other fueling stations, fleets of trucks (termed "fleet fueling") construction sites (termed "wet hosing") or other locations as requested by their customers. Within the diesel industry, the major oil companies are trying to decrease direct contact with the end consumer; this forces the marketers to interact directly with the customer. Analogous to other freight industries, marketers operate as a typical carrier, but they also operate as a supplier, as the product becomes their proprietary responsibility once they purchase it from the major oil company until they sell it to the customer. This gives them an incentive to look for the lowest price in their purchase of diesel, not just to minimize transportation costs by picking up from the closest facility. In addition, marketers can contract directly with the major oil companies to transport diesel to a direct customer of the major oil company. In this sense the marketer operates as a carrier only.

5.3.4.6 Fuel Price Variability

The past 36 months have seen tremendous fluctuation in the selling price of diesel on the market, as well as in the price of diesel at terminal locations. For example, the price of diesel at terminals in Pasco is sensitive to the mode of transportation that offloads at the terminal (pipeline or barge) because the fluctuation in the price of diesel not only affects the raw sale price of diesel but also the cost of transportation of the diesel. These fluctuations can cause diesel prices to change hourly, with 5- to 15-cent price fluctuations at a single terminal location per day. As a result, the marketers are constantly monitoring the price at each terminal and re-routing origin-destination trips in real time in order to take advantage of the lowest instantaneous terminal price, given their fixed and variable transportation and inventory costs. Often the shortest trip between an origin terminal and a destination location is not utilized because greater costs can be saved by traveling a greater distance to a terminal that has a lower diesel selling price.

For instance, assume that the sale price of diesel at a terminal in Tacoma is $3.05 per gallon in comparison to $3.00 per gallon at a terminal in Seattle. A Tacoma-based marketer needs to make a 10,000-gallon delivery to a customer in Auburn. The transportation costs from Tacoma to Auburn are $200, while those from Tacoma to Seattle and then to Auburn are $400. Thus the total trip price from the Tacoma terminal would be $30,700, while that from Seattle would be $30,400. With a cost savings of $300 to pull diesel from the Seattle terminal rather than the Tacoma terminal, the marketer will take the longer trip and utilize the terminal in Seattle. Refer to Figure 5.21 and Table 5.15.

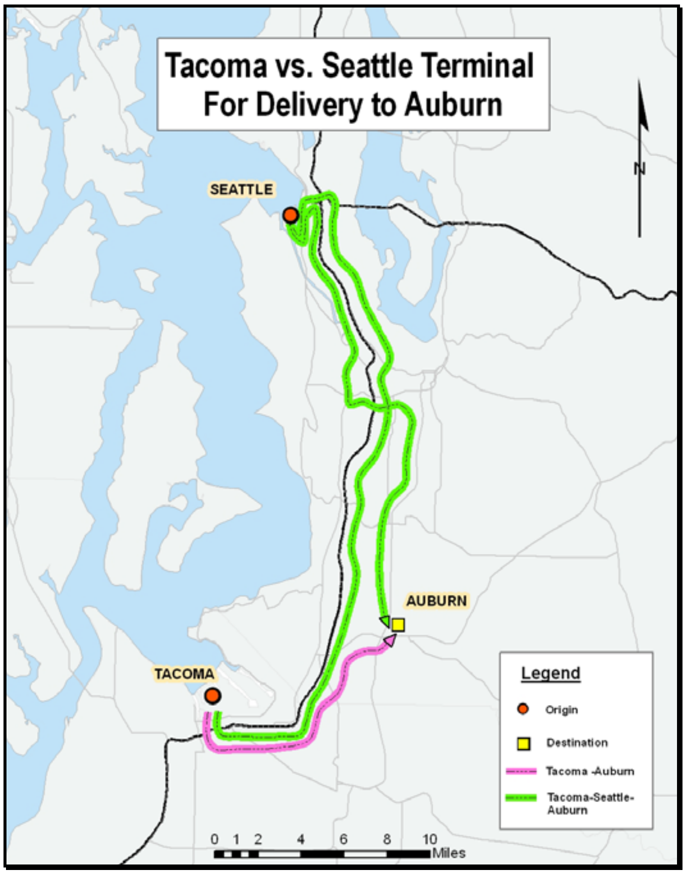


Figure 5.21. Tacoma or Seattle to Auburn diesel delivery

Table 5.15. Tacoma vs. Seattle terminal for delivery to Auburn

	Tacoma Terminal	Seattle Terminal
Diesel (Gallons)	10,000	10,000
Product Price (per Gal)	$3.05	$3.00
Total Product Price	$30,500	$30,000
Transportation Costs	$200	$400
Total Cost of Delivery	$30,700	$30,400

A typical tanker truck includes both the truck and a trailer. The combined volume of the entire truck-trailer usually exceeds 10,000 gallons; however, because of WSDOT weight restrictions on the road network, a single tanker truck can haul up to 10,000 gallons of diesel. Figure 5.22 shows a typical tanker truck with trailer.

Figure 5.22 Tanker truck with trailer

Diesel delivery is similar to just-in-time (JIT) delivery. Although some customers might have pre-set delivery dates or an automatic request for delivery technology in place, most customers requiring diesel will place an order with a marketer as demand requires, and the marketer will make the delivery. Some marketers have the capacity to store inventory, but most deliveries require the marketer to pull diesel directly from a terminal and then make the delivery. A tanker truck can load diesel at a terminal at a rate of 600 to 800 gallons per minute. Marketers prefer to maximize each trip by being efficient with their deliveries. If possible, they will try to combine deliveries in order to avoid deadheading and will also make multiple deliveries on a single trip if needed.

5.3.5 Network Vulnerability and Reliability

To map the distribution of diesel by truck in Washington state, we began by identifying the closest terminal (shortest travel time on the network) to each cardlock facility. The Tele Atlas street network permits a number of restrictions. For the diesel case study, all of the restrictions were enabled, including ferry restrictions. U-turns were allowed only at dead ends. With origins and destinations matched, we defined the preferred service area for each terminal, assuming that the price for diesel was the same at each terminal.

A map showing the association of each origin to a destination and the resulting service areas is shown in Figure 5.23. Although the figure shows only cardlock facilities, these service areas reflect all diesel distribution locations, since the 27 terminals reflect the entire population of terminals in the state. Note that in this case, without disruption, and assuming constant diesel pricing, there are essentially no cross-Cascades trips of diesel trucks. This is in striking contrast to the potato industry, which relies on cross-Cascades routes.

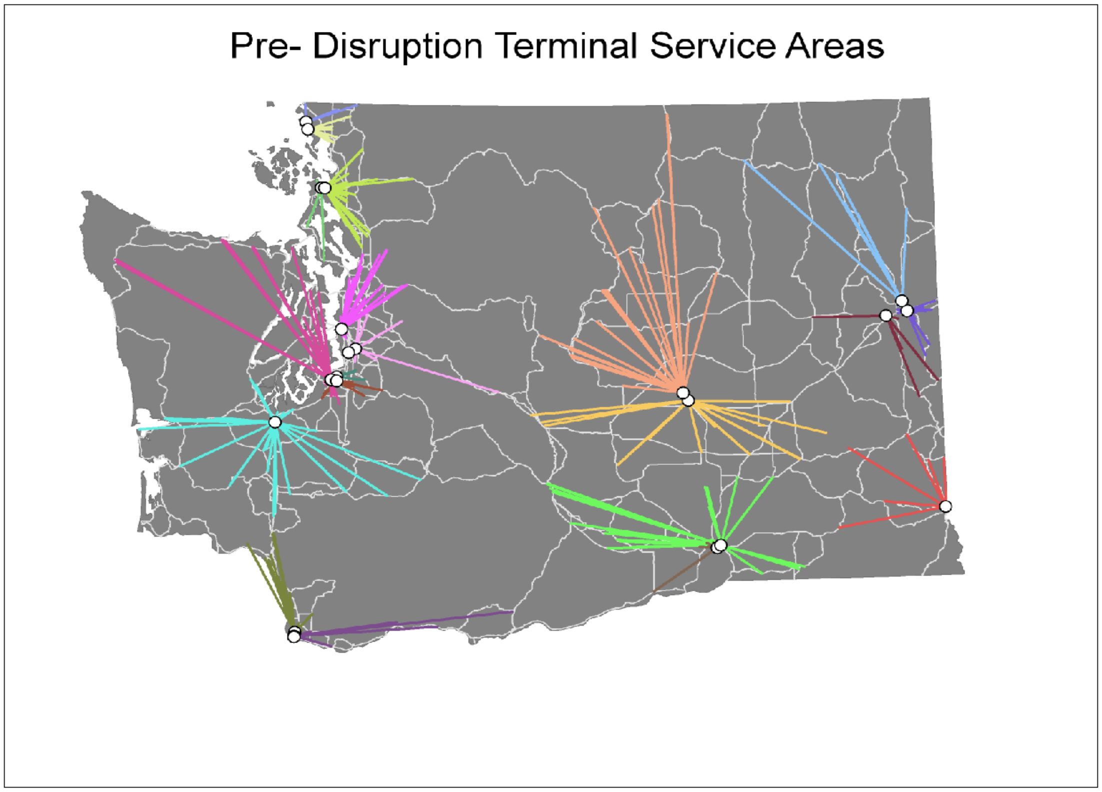


Figure 5.23. Terminal service areas pre-disruption

Figure 5.24 shows the number of origin-destination pairs that use each link in the network, where origins are terminals and destinations are cardlock racks. Again, essentially no trucks in the diesel distribution system use the cross-Cascades routes in the base case. However, some links service almost 40 origin-destination pairs. Of high importance are Highway 16 on the east side of the Olympic Peninsula and Highway 17/282 out of Moses Lake.

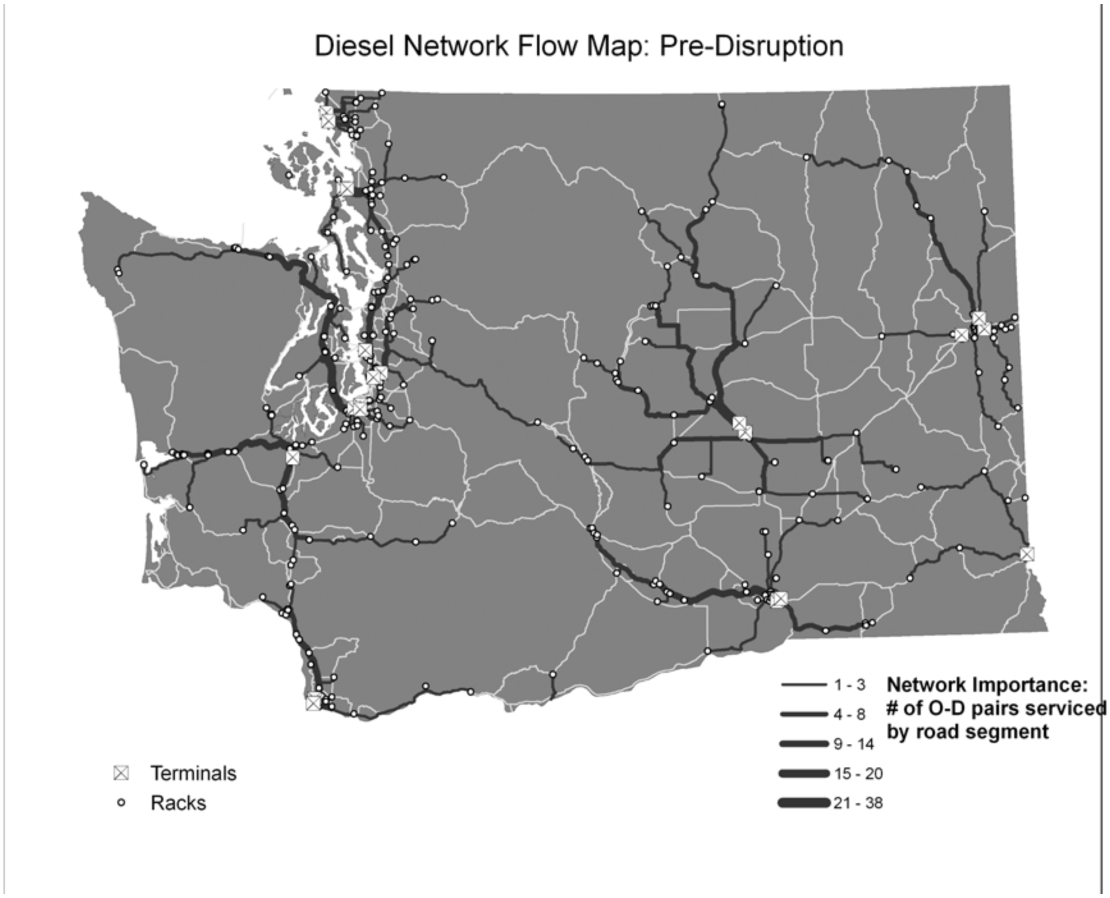


Figure 5.24. Diesel network flow map showing the number of origin-destination pairs using each link

Given this, the impact of a 2-hour closure of the cross-Cascades routes would be zero. It is of particular interest that the diesel distribution system is less impacted by a cross-Cascades corridor closure than the potato distribution system. In fact, it is not affected at all. Recall from Figure 5.16 that diesel essentially avoids trucks and moves from the boundaries of the state inland by pipeline or barge. Only the final leg of the distribution system uses trucks. Given the accessibility provided by the coast, the

Columbia River, and the existing pipeline infrastructure, the Cascades routes are not critical to the diesel distribution system under normal operations.

An incident along the UDN will have far different effects on the network as a whole than an incident along the road network. The two elements of the UDN (pipeline and waterway) are the primary arterial that, in a redundant manner, feeds the road network portion of the distribution system. In the case of potato distribution, the UDN is served by roadways. This makes the diesel distribution system much less vulnerable to roadway disruptions than the potato distribution system.

It could be argued that the UDN has more redundancy than the road network because it contains two distinct modes of transportation that are susceptible to different types of incidents but that are capable of providing similar distribution between the origin and destination of the UDN (although at different flow rates). For instance, scheduled maintenance or a closure of a section of the pipeline because of an event of interdiction does not directly preclude distribution by means of the waterway network. Similarly, inclement weather that prohibits waterway movements or maintenance operations at the locks along the Columbia and Snake rivers does not directly affect pipeline operations.

The benefits of a redundant system were realized in 1999 when the Olympic Pipeline was shut down between Ferndale and Anacortes for 18 months because of a gas leak. During this time, diesel was transported via barge and tanker truck from the Ferndale refineries to the Anacortes refineries, where the pipeline was charged and supply maintained.

For analysis we considered a disruption to the Moses Lake terminals on the Yellowstone Pipeline. The Moses Lake terminals, the cardlocks they serve, and the least cost routes are shown in Figure 5.25. These terminals serve cardlock facilities in the center of the state. If these terminals were shut down, these cardlock facilities would need to be served from alternative terminals. We removed these terminals from consideration and matched these cardlock facilities with the next closest facility.

ArcGIS does not provide a tool to aggregate the individual O-D shortest routes, and consequently, there is no simple way to determine the importance of any particular road segment to any particular industry. Therefore, these routes must be joined to another street layer—preferably one that is composed of short rather than long road segments (allowing greater accuracy in the analysis). A problem arises, however, because the size of a complete street dataset with short segments easily overwhelms most PC processors. A work-around has been devised to overcome this challenge. It requires the GIS to interface with Microsoft Access and requires that each route be handled separately. If future case studies are anticipated, this process should be automated.

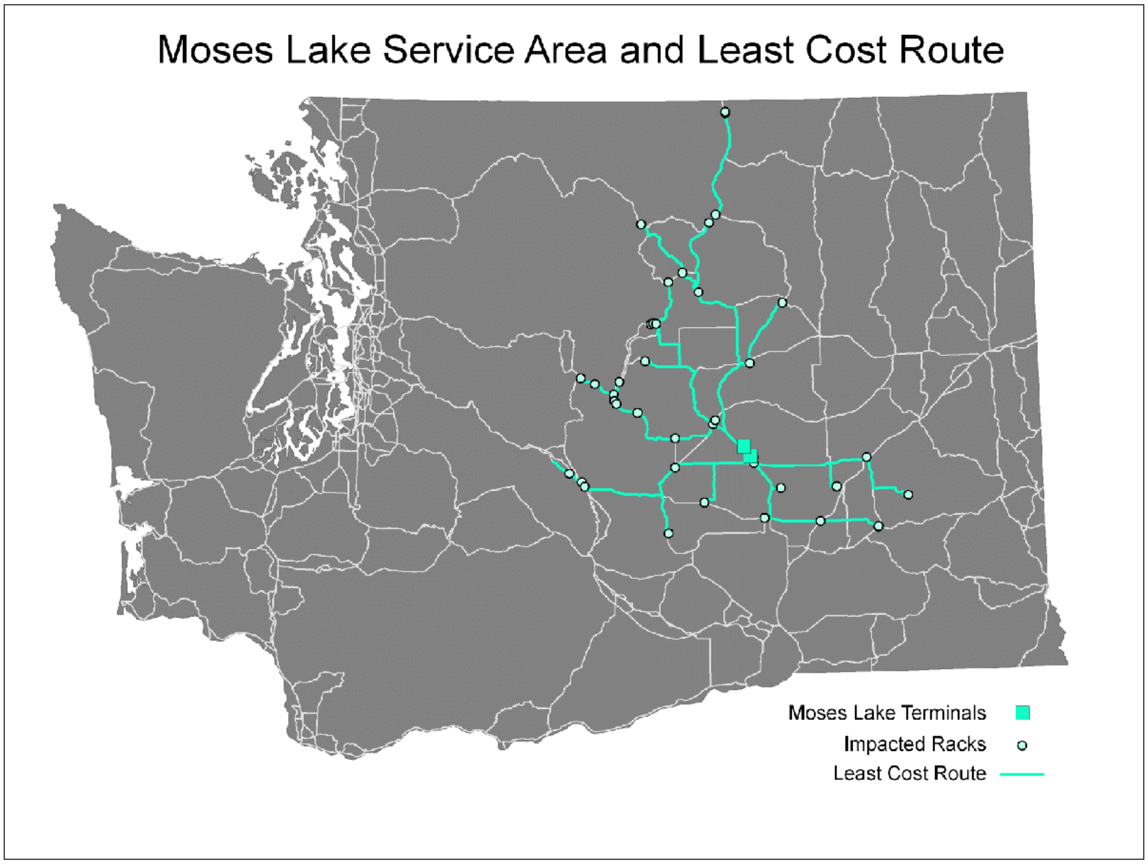


Figure 5.25. Moses Lake terminals, service area, and least cost route

Figure 5.26 shows the reassignment of these cardlock facilities to other terminals. These are the terminals with the shortest travel time, assuming that Moses Lake terminals were unavailable.

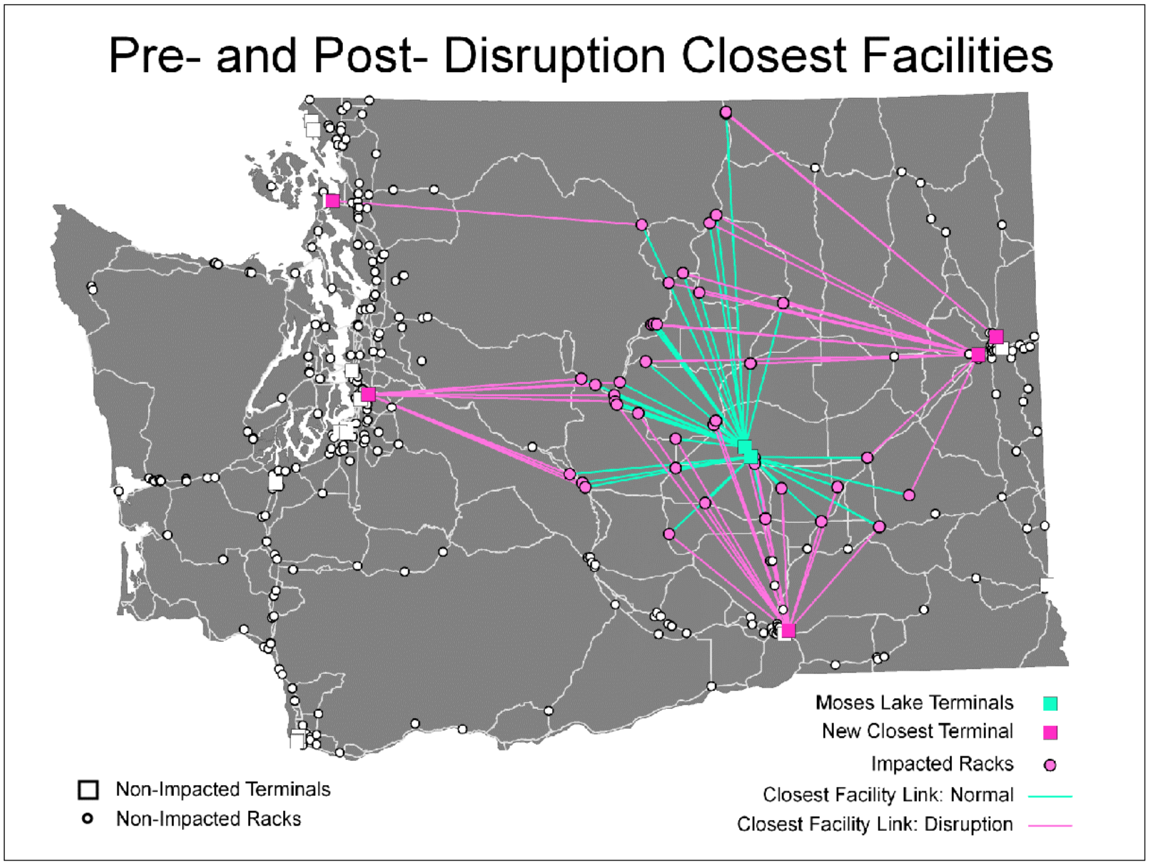


Figure 5.26. Closest terminals to cardlocks initially served by Moses Lake, if Moses Lake shut down

Figure 5.27 shows the new terminal service areas, assuming that the Moses Lake terminals were shut down. Notice now that terminals along the western edge of the state would service cardlock facilities on the east side of the Cascades, and terminals on the east side of the state would have service areas that stretched farther to the west.

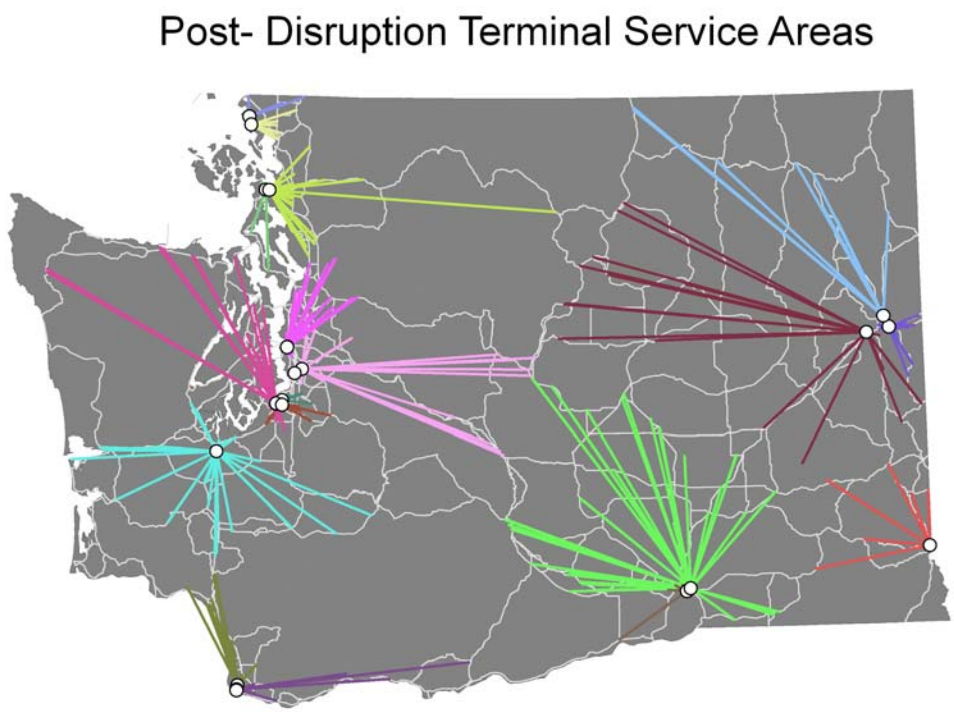


Figure 5.27. Terminal service areas with Moses Lake terminals shut down

Figure 5.28 shows the specific routes that would be used to service the cardlock facilities if the Moses Lake terminals were removed. Figure 5.29 shows the number of terminal-cardlock pairs using each link in the network after closure of the Moses Lake terminals. Notice that now the cross-Cascades routes would be critical to the distribution system. In particular, I-90 would be one of the most important links. Also notice that some links would be more critical to the distribution system, carrying fuel for almost 50 origin-destination pairs.

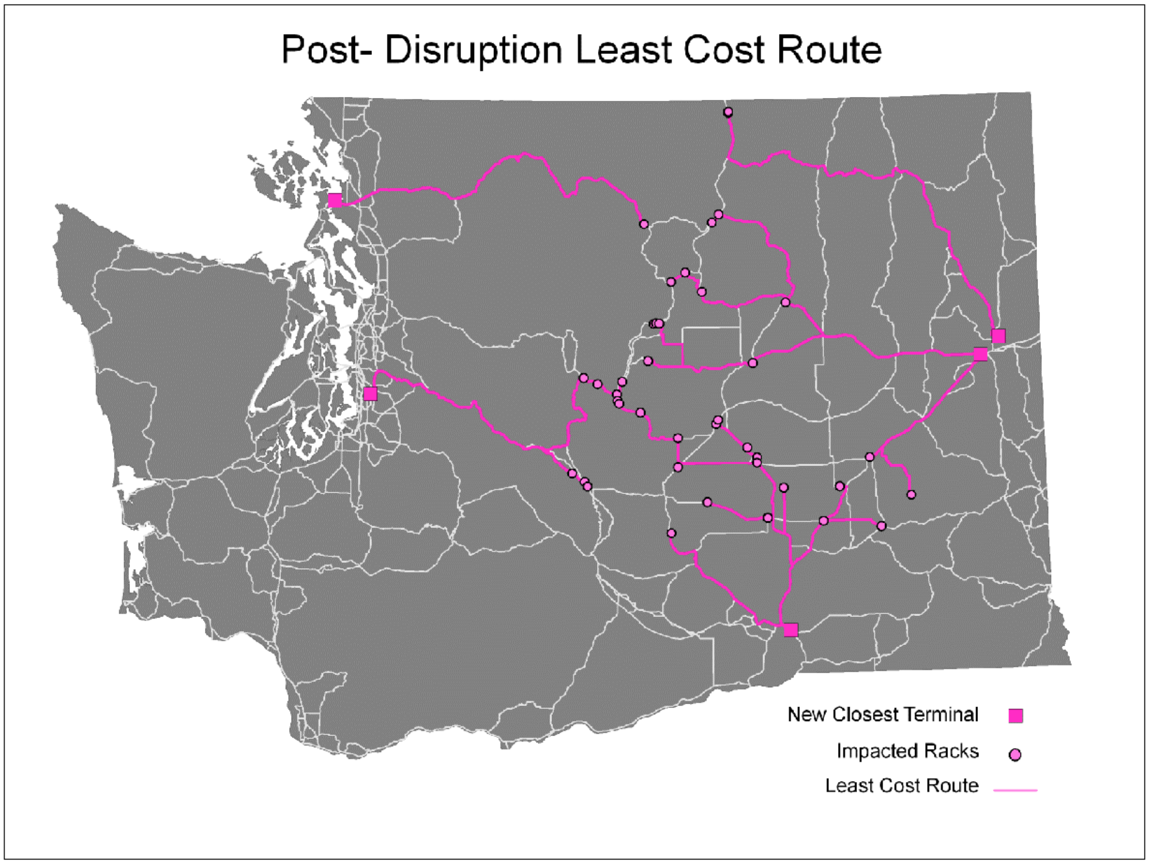


Figure 5.28. Least travel time terminal-cardlock pairs without the Moses Lake terminals

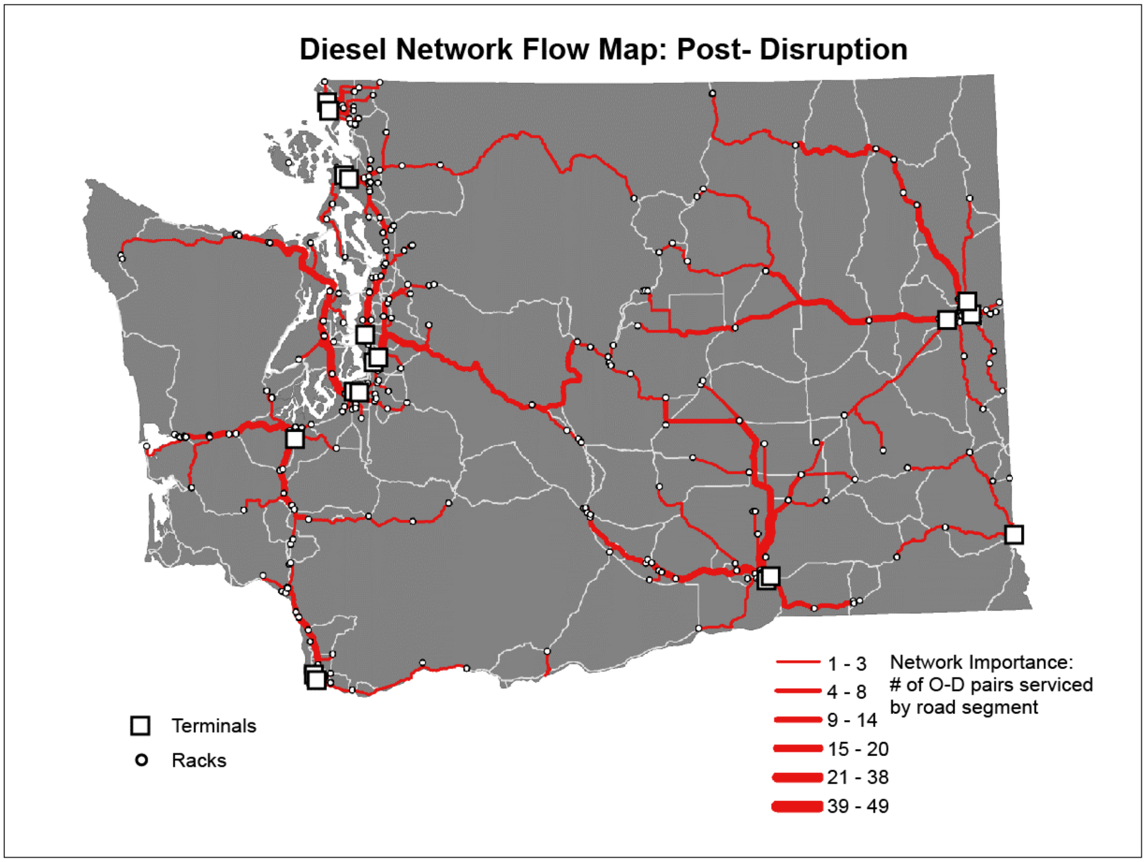


Figure 5.29. Number of terminal-cardlock pairs using each link with Moses Lake terminals shut

Figure 5.30 shows a comparison of flow between terminals and cardlock facilities before and after the Moses Lake terminal closures. Notice the importance of I-90 routes and the significance of 395 out of the Tri-cities area.

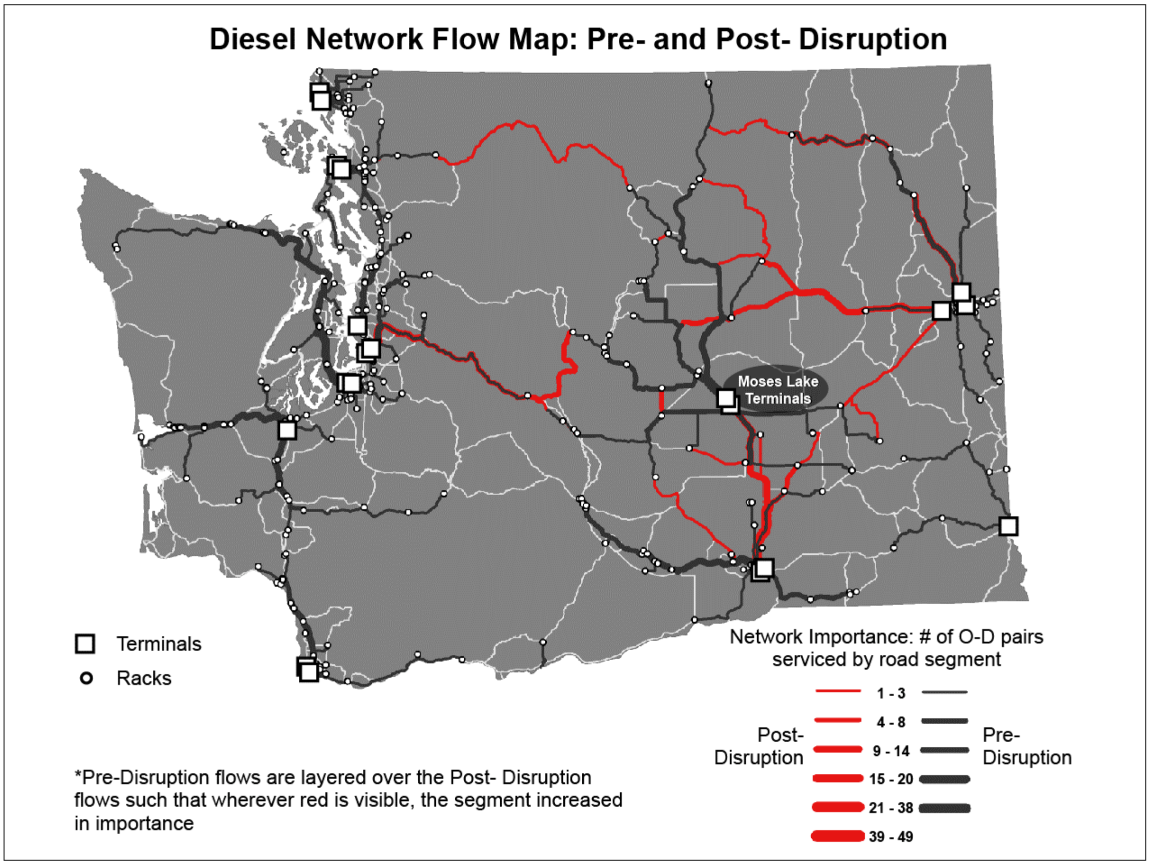


Figure 5.30. Comparison of flow between terminals and cardlock facilities with and without the Moses Lake terminals

We can summarize the effects of this disruption with some additional statistics:

1. The total truck miles required to service each rack once from the closest terminal is 10,676 miles under normal conditions, and would be 12,640 miles with the Moses Lake terminals removed. This is an increase of 18 percent.
2. Under normal conditions, there are four terminal-cardlock pairs from which the network distance is greater than 140 miles; without the Moses Lake terminals, this number would increase to 11 pairs.
3. Under normal conditions, there are 16 terminal-cardlock pairs from which the network distance is greater than 100 miles; without the Moses Lake terminals this number would increase to 35 pairs.

4. Under normal conditions, the longest trip required to service a cardlock from a terminal is 162 miles; this would increase to 177 miles without the Moses Lake terminals, an increase of 9 percent.
5. Under normal conditions, the average trip length is 34 miles; this would increase to 41 miles without the Moses Lake terminals, an increase of 20 percent.
6. Under normal conditions, 43 cardlock facilities are serviced by the Moses Lake terminals. A summary of the impact of the disruption for each cardlock facility is provided in Table 5.16.

We can also observe that the bulk of the racks (40 of 43) serviced by the Moses Lake terminals would be re-routed to only three other terminals (and nearly half of these (19 of 40) would be re-routed to terminal 4420—located in Pasco).

The network is very robust. The Moses Lakes terminals were selected for evaluation because they are the only terminals that do not have any realistic redundancy in their supply (it all comes via pipeline), as barges cannot access Moses Lake. Even in these circumstances, it could be argued that the impact on the distribution system would be minimal. Given marketers sensitivity to price, they currently have very flexible operations; they regularly source from different terminals, affecting the routes and travel times. This requires them to have a level of flexibility in numbers of drivers and trucks that other industries do not. As discussed with respect to enterprises and resilience, this exposure to sourcing risk gives them a natural flexibility that positions them well for responding to disruptions such as a shut-down of the Moses Lake terminals.

What we do not have sufficient information to consider is the availability of additional diesel storage and truck capacity, which would be required to sustain normal flow under these conditions.

Table 5.16 Impact of shut-down of Moses Lake terminals on each cardlock originally serviced by those terminals

NEW ROUTE		Disrupted		Normal		Difference	
rack	terminal	Minutes	Miles	Minutes	Miles	Minutes	Miles
256	4404	186.29	148.46	88.18	63.52	98.11	84.94
259	4404	191.13	152.61	95.97	70.20	95.16	82.41
253	4404	183.42	146.56	92.48	67.20	90.94	79.36
251	4404	172.17	138.17	103.68	75.54	68.49	62.64
242	4404	163.53	132.12	110.92	81.36	52.62	50.76
244	4404	125.99	109.65	81.24	70.77	44.75	38.88
243	4404	122.08	107.37	85.16	73.05	36.92	34.31
241	4404	115.07	101.52	88.33	78.14	26.74	23.38
290	4412	238.53	176.82	220.08	151.61	18.46	25.20
291	4412	239.21	177.42	220.75	152.22	18.46	25.20
292	4420	106.68	79.22	0.58	0.33	106.10	78.89
286	4420	125.80	92.88	21.94	14.78	103.86	78.10
288	4420	127.59	94.10	23.73	16.01	103.86	78.10
257	4420	184.63	139.35	86.06	62.28	98.56	77.07
260	4420	171.83	130.34	73.27	53.27	98.56	77.07
279	4420	143.47	108.86	44.91	31.79	98.56	77.07
296	4420	98.61	73.78	3.50	2.27	95.11	71.51
278	4420	128.94	101.05	36.01	29.85	92.92	71.20
297	4420	95.46	71.40	5.62	3.39	89.84	68.01
283	4420	98.62	73.82	50.35	32.50	48.27	41.32
315	4420	82.58	57.08	25.94	17.80	56.64	39.28
325	4420	86.74	66.21	55.57	41.73	31.17	24.47
327	4420	86.37	66.12	55.65	41.82	30.72	24.31
300	4420	68.24	50.82	38.84	28.13	29.40	22.69
301	4420	67.75	50.61	38.35	27.93	29.40	22.69
273	4420	108.27	66.20	74.82	57.20	33.45	9.00
319	4420	61.56	48.22	59.88	44.19	1.68	4.03
335	4420	90.97	70.08	89.55	66.24	1.42	3.84
336	4420	90.68	70.07	89.26	66.23	1.42	3.84
262	4426	176.94	132.30	92.93	60.92	84.01	71.38
263	4426	209.04	146.39	125.03	75.02	84.01	71.38
265	4426	207.61	145.26	123.60	73.89	84.01	71.38
268	4426	205.99	144.17	121.98	72.79	84.01	71.38
295	4426	120.47	89.95	56.30	41.95	64.17	48.00
275	4426	208.87	136.51	145.45	90.57	63.43	45.94
282	4426	180.51	118.69	117.25	76.93	63.26	41.76
280	4426	200.91	130.62	137.64	88.86	63.26	41.76
285	4426	214.24	138.72	161.48	107.37	52.76	31.34
289	4426	208.70	134.90	166.25	111.28	42.44	23.62
330	4426	67.77	59.30	51.96	44.63	15.81	14.67
317	4426	115.96	81.07	101.87	68.79	14.09	12.27
339	4426	118.68	78.16	109.48	72.95	9.20	5.21
261	4428	203.32	151.81	185.06	116.85	18.26	34.96

5.4. CONCLUSIONS

A closure of the Cascade corridor would have NO effect on diesel distribution in Washington state. This demonstrates the value of understanding how different industries use the infrastructure. Without these case studies we would have to assume that a closure would affect the industries similarly, and it would likely be assumed that diesel trucks would be harder hit because of the necessity of the product for the economy.

The diesel supply system is susceptible to disruptions along the network, but the type and severity of the disruption is dependent on the mode of transportation. On the UDN side, disruptions in the network directly affect the supply of diesel that can be distributed by marketers along the road network to the consumer and have significant consequences. On the road network side, disruptions to a roadway link can be accommodated more readily. Marketers are practiced at changing their operations regularly because of price variations of diesel at terminals. The network can be likened to a tree. In this case the trunk represents barge and pipeline transport, and the branches represent trucks. It is much easier to disrupt the flow by severing the trunk than the branches.

In the case of potato distribution, all of the transportation takes place via truck, and the industry is therefore more dependent on that mode. Also, the industry is not exposed enough to other uncertainties to warrant building more flexibility into operations.

Unlike the potato industry, diesel marketers operate under significant time constraints and own the fuel in their trucks. This gives them additional incentive to re-route in the face of a disruption. They are responsible for the inventory cost of the fuel, and at a delivery frequency of two to three times per week, delays quickly become problematic in terms of the availability of fuel. In the case that marketers are delivering to their own cardlock facilities, shortages mean their own lost business opportunities. In addition, their operations are designed for some flexibility.

There is essentially no short-term substitution in the case of diesel, beyond the direct costs of rerouting if there is a shortage at a particular location. Demand can be difficult to predict in the case of disruptions and is often depressed, making lost sales opportunities less likely. There is little concern about long-term substitution, whereas for potatoes, products that are less subject to disruption may be preferred. Competition between marketers is fierce but is not expected to come into play, as all marketers will face the same challenges in the case of rare disruptions.

In short, the diesel distribution system is surprisingly resilient to roadway disruption, is likely to quickly re-route, and can face the direct costs of additional transportation with limited secondary economic effects.

6. STATEWIDE FREIGHT MODEL RECOMMENDATIONS

Increasingly complex questions regarding the interaction between the state's transportation infrastructure, transportation policies, and economic system require increasingly sophisticated tools. This report documents an effort to develop a statewide GIS tool for mapping supply chains and to evaluate the impacts of disruptions to the transportation system on specific industries. In the future, WSDOT would like to be able to estimate the impacts on a broader set of industries, with a more automated tool that can capture an increasingly large set of complexities. To do this, a more complete statewide freight model is required, one that has data for a complete cross-section of industries and that addresses additional complexities in the statewide freight system.

After completing the work described in this report, the researchers are in a position to recommend a methodology, scope, data sources, and long-term management plans for such a model. Over the last 18 months, two meetings were held to gather stakeholder input. One meeting was held with model users, including MPOs, DOT offices, and Washington ports, to discuss their needs for a model and their preferences for its design. A second meeting was held with WSDOT planning and freight office staff to discuss internal WSDOT preferences and needs. These meetings are summarized more fully in the appendix. In addition, the researchers conducted an exhaustive review of existing models, developed the existing GIS model, and conducted two case studies. The researchers are also active in the national dialogue about methods to develop the sub-national commodity flow databases that would be required to feed such a model.

6.1 MOTIVATION

It is clear that the need for such a model comes from the desire to prioritize investments on the basis of economic value to the state. Current tools and methods use other metrics, such as congestion reduction, flow on affected routes, and level of service, to prioritize investments. Input from both the freight community and the planning community, as well as all regions of the state, made clear that the objective of a statewide freight model is to allocate funds to the projects that will bring most economic benefit to the state. This should be done both for individual projects and to prioritize portfolios of projects.

6.2 INTEGRATION INTO STATEWIDE PLANNING

It is critical that the model have executive level buy-in. Investment in a model that is not fully utilized is a waste of public funds. Prior to investing in a model, decisions should be made about where the model is to be housed and who will maintain it. This group must have the financial ability to maintain the model and its data so that it can be trusted to assist with investment decisions. Use of the model must be fully integrated into the statewide transportation planning process.

We recommend that the model be housed by a university research organization. This group would have the intellectual capital to improve the model, and, unlike a consulting firm, would lack proprietary interest in controlling the model. Such a group would also possess the computing power to house the model and the model's supporting data.

6.3 USE OF THE MODEL

Stakeholders indicated that they would like to run the model themselves. This would require a significant investment not just in model capacity but also in developing a user interface so that the model can be used by "untrained" users. We do not suggest the model be usable by a broad spectrum of users but do suggest that resources be made available to allow the owners of the model to work with clients to exercise the model for their purposes.

6.4 SUB-NATIONAL COMMODITY FLOW DATA

We recommend the WSDOT continue to work with national organizations such as the Transportation Research Board to pool national and state-level resources to develop a methodology for collecting sub-national data. This would be the level of information required to support a statewide freight model. The data need to provide corridor-specific commodity flow information and should associate that information with industry sectors. The spatial resolution of the data should be the zip code.

"Corridor-specific" does not imply that industry-specific information would be available for every road segment but rather would be available for corridors identified as important to the state freight transportation system. Commodity data would not be so specific that they could differentiate between types of potato products, but agricultural products would be separated from manufactured products and service vehicles. The data should capture out-of-state markets and generators, as well as intrastate flows.

6.5 METHODOLOGY

We do not recommend a simulation model at a statewide level. While this may be useful at a regional level for analysis of specific corridors or districts, it is not necessary at the state level. The stakeholders made it clear that the purpose of the statewide freight model would be to connect regions within the state, whereas the jurisdictions within a region would be responsible for doing smaller scale, regional modeling.

Instead we recommend a GIS-based network model supported by sub-national commodity flow data. Spatial resolution would be intended to support inter-regional travel, not to model flow on every road in the state.

The model would have an economics impacts module that would use a general equilibrium model to estimate the economic impacts of disruptions to the transportation system.

The model should capture time of day effects from congestion, as well as seasonal differences in commodity flows. This could be done by developing commodity flow data by season and running the model separately, and for congestion, by including link capacities and link cost functions that are a function of flow along that link. The model should include the entire roadway system, but analysis is not recommended at this level of spatial detail.

6.6 RESOURCES REQUIRED

The methodology selected to date supports an incremental program for model improvement. It is unreasonable to think that at this point we would invest $1.5 million in a statewide freight model. Rather, we suggest annual investments in the model so that over the next 5 years, through shared investments by the WSDOT, the Transportation Research Board, and Transportation Northwest (TransNow), a comprehensive statewide freight model can be developed.

7. SUMMARY AND CONCLUSIONS

7.1 SUMMARY

This report presents a significant contribution to the body of knowledge regarding freight transportation system resilience. To this we have contributed the following:

- a framework for considering the resilience of the freight transportation system
- an understanding of current supply chain responses to transportation disruptions
- a framework for defining supply chain responses to transportation disruptions
- a multimodal GIS representation of the Washington state freight network with embedded link and node operating logic
- an understanding of the current data and a methodology used for freight planning in the state and the desires of the freight planning community moving forward
- two case studies that demonstrate the different uses of the infrastructure by industries and the data requirements of such detailed supply chain mapping.

7.2 FUTURE WORK

7.2.1 Improve link cost functions for freight, flow, and congestion

The link cost functions currently embedded in the model and used for routing are the same as those used by TeleAtlas, the supplier of GIS networks for Google Maps. These are travel times primarily derived from distance and speed limit data, but with some undefined congestion factors for urban areas. These are state-of-the-art for routing tools but are likely not reflective of travel times for trucks on all routes, in particular, rural mountain highways. We suggest improving these link cost functions to capture 1) passenger travel, 2) congestion effects, and 3) observed travel times from trucks. Observed travel times for trucks can be gleaned from WSDOT's Truck Performance Measures project ongoing with WSDOT, the University of Washington, and the Washington Trucking Associations.

7.2.2 Characterize supply chains with similar logistical behavior

We do not recommend moving forward by mapping all supply chains in this fashion; however, priority industries and industries with different supply chain typologies, should be mapped. Research should be done to classify supply chains into those with similar logistics, generating a supply chain typology. Representative supply chains in each category should be studied.

7.2.3 Prioritize industries important to Washington state and do additional case studies

The case studies provide invaluable information about the industries and their use of the transportation system. There are probably a small number of industries that can be identified as important to the state and pursued.

7.2.4 Map freight generators

Begin by defining a freight generator. We have demonstrated that significant benefit can be derived from mapping the fixed infrastructure. In the absence of flow information, mapping the origins and destinations still provides significant benefit and understanding of the value of different links to different industries. GPS data available from the Truck Performance Measures project can assist in mapping these freight generators. Using the existing tool, locations with single access points of failure can be identified.

7.2.5 Build an automated tool within GIS to map O-D pairs on infrastructure

With freight generators mapped and this automated tool, the analysis completed for the diesel case study could be repeated for other industries.

7.2.6 Integrate GPS data from the Truck Performance Measures project

The Truck Performance Measures data have been mentioned several times in support of freight generator mapping and improving link cost functions. In the future, we see many possibilities for collaboration between these two projects.

7.2.7 Work closely with regional agency partners to ensure compatability

Stakeholders made it clear that the statewide freight model should connect with regional models. In addition, regional MPOs such as the Puget Sound Regional Council have extensive experience with models and integrating models into planning.

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APPENDIX A: ACRONYMS

AST – above-ground storage tanks

CFN – Commercial Fueling Network

CFS – Commodity Flow Survey

CSI – Container Security Initiative

C-TPAT – Customs-Trade Partnership Against Terrorism

CVS – commercial vehicle survey

DOA – Washington State Department of Agriculture

DOL – Washington State Department of Licensing

DOR – Washington State Department of Revenue

ECY – Washington State Department of Ecology

EIA – Energy Information Administration

EPA – Environmental Protection Agency FAF2 – Freight Analysis Framework

FERC – Federal Energy Regulatory Commission

FGTS – Washington State Freight and Goods Transportation System

FHWA – Federal Highway Administration

FMCSA – Federal Motor Carrier Safety Administration

FSRP – Freight System Resiliency Plan

FTS – freight transportation system

GIS – geographic information system

GPS – Global Positioning System

HAZMAT – hazardous material

I/O – input/output

JIT – just-in-time delivery

MPO – metropolitan planning organization

O-D – origin-destination

OEA – Office of External Affairs

PHMSA – Pipeline and Hazardous Material Safety Administration

PNWA – Pacific Northwest Waterways Association

PSRC – Puget Sound Regional Council

SCGE – Spatial Computable General Equilibrium

SFTA – Strategic Freight Transportation Analysis

SMA – statistical metropolitan area

UDN – Upper Distribution Network

USDA – United States Department of Agriculture

USDOT – United States Department of Transportation

UST – underground storage tank

VIUS – Vehicle Inventory and Use Survey

WSDOT – Washington State Department of Transportation

WTA – Washington Trucking Associations

APPENDIX B: CONTACTING MARKETERS

1. Washington Oil Marketers

Estimate of average number of gallons carried by fuel truck (10,000).

Mentioned that Southwestern Washington would benefit from another pipeline corridor, but that the economics aren't conducive to such a project. Costs associated with meeting environmental regulations, fighting legal challenges to site placement decisions, etc. make building new capacity cost prohibitive. Also mentioned that there is little to no extra capacity built into the state's fuel distribution system.

80% Claim:

Don't believe that the 80% market share for our initial seven distributors is correct. There is far too much movement in Eastern Washington to justify 80% covered by the seven. All seven mostly operate in Western Washington, so maybe they cover 80% of the movements on this side of the state.

Origin Locations:

- NW Washington (Everett and north) will pull directly from the refineries.
- South of Everett and east to Issaquah will pull from the Harbor Island rack (from Olympic Pipeline)
- Kitsap Peninsula will pull from Harbor Island, Renton, or Tacoma racks (from Olympic Pipeline)
-SW Washington will pull from the Willbridge Terminal (rack) in Portland (from Olympic Pipeline)
- NE Washington will pull from Moses Lake rack or sometimes Spokane (from Yellowstone and/or Chevron Pipeline)
- Central Washington will pull from Moses Lake or other Western Washington racks
- SE Washington will pull from Pasco (Chevron Pipeline or via barge), Moses Lake or Spokane racks

Marketers and Majors Relationship:

All marketers are independent small to medium sized companies. The marketers enter into an agreement/contract with the major oil companies in order to acquire fuel so that the marketers can deliver to their customers (not the major's customers). In this sense, the marketers work for their customers, but get their product from the majors. The majors dictate who gets what product and from where, and it can be arbitrary (in the eyes of the marketers). With this, the marketers are constantly changing operations to meet their customer's demand while keeping up with the availability and prices set by the majors.

For example, a marketer in Central Washington may decide to get their diesel from Harbor Island rather than Moses Lake because the cost of diesel at Moses Lake is 30 cents more than at Harbor Island based on how the majors have set the price. Even though the trip is longer to the Harbor Island rack, the cost/benefit is less and thus the marketer will change their operations in order to capture the efficiency.

Refineries and Pipelines:
Each refinery shuts down for at least 30 days every year. The reason for this is annual maintenance. However, the refineries work together to ensure that not more than one is shut down at any given time. But sometimes when a refinery tries to come back online they find that they can't (for whatever reason), and need another 30 days.

Also, the pipeline can be shut down for maintenance. Usually it is not for more than a week at a time, and usually does not require the entire pipeline to be shut off. Everything upstream of the maintenance location still operates. The Olympic Pipeline Company is not required to notify the marketers when they are performing maintenance, they find out when they show up to the rack and there isn't any diesel left.

2. Marketer #1

This marketer delivered 36,000,000 gallons of diesel last year, which is in the neighborhood of 2% of the diesel refined in the state.

a. What are your origin locations (fuel racks) for diesel product?

Anacortes (Shell and Tesoro), Seattle (Harbor Island), Tacoma

b. For each origin, what is your list of delivery locations (or delivery area for each origin)? Anacortes-N. Puget Sound, Skagit County, Snohomish county Seattle-Seattle, E King County, S King County Tacoma-Tacoma, Pierce County, Olympia

Destination could be customer or storage tank

Storage tanks at CFN cardlocks in:

Granite Falls 40,000 gallons

Covington 25,000 gallons

Arlington 70,000 gallons

Lynwood 10,000 gallons

Everett (2) combined 300,000 gallons

c. Does the truck deliver to multiple destinations during each delivery route?

Yes

d. Do your routes usually follow the shortest distance between origin and destination? If not, why not? Yes

e. Please list the top five (by volume) highway segments (from onramp to exit) you route over.

Exit 192-our storage, railroad (major customer), Exit 163-Harbor Island, multiple customers, Exit 208-our Arlington Plant, Exit 136 –Tacoma, railyard, Exit 230-Anacortes

f. What is your delivery cycle for each delivery location (daily, weekly, etc)?

Daily-railyard, Weekly-most regular customers, others vary by season

g. What is the capacity of your vehicle's tanks?

4500-tanker (15), 10,000-truck trailer (6)

h. What volume of diesel do you deliver during each visit (either in truckloads or volume of diesel)? 100-10000 gallons

i. Does this amount vary over each delivery? Why? By how much? Yes, depending on size of demand and customers

ii. Does this require a full truck-load? Sometimes, sometimes more (particulary in the case of boats)

i. What is the capacity of the storage tanks at each of your destinations?

Everett-300,000 gallons + 90,000 lube tanks, Arlington-70,000 (see b above)

j. Do you have an information management system that could provide us with this information for the last year? Yes, depending on the questions

36,000,000 gallons of diesel delivered last year

k. Is each destination always served by the same origin? Why or why not?

Usually

l. What is your company's share of the diesel delivery market in the state?

Unknown

Marketer #2

1. *What are your origin locations (fuel racks) for diesel product?*

   "We pick up from the major refineries in Anacortes, Seattle, Tacoma, Vancouver, and Portland, OR. We also pick up from Pasco, Moses Lake, and Spokane."

2. *For each origin, what is your list of delivery locations (alternatively ask for delivery area for each origin)?*

   "You could draw a 70 mile circle around each terminal, and that would roughly cover our service area. We take a close look at the cost of product when we decide where to pick up and how we distribute. A lot of product goes east of Seattle"

3. *Does the truck deliver to multiple destinations during each delivery route?*

   "No. We pick up a full load and drop off a full load. Even in an emergency situation, split loads would still tend to be counterproductive."

4. *Do your routes usually follow the shortest distance between origin and destination? If not, why not?*

   "Yes. We always take the shortest, most direct route possible."

5. *Please list the top five (by volume) highway segments (from onramp to exit) you route over.*

   "I don't know the specific top five segments, offhand. In terms of gasoline distribution, the high-density population areas are served by the 'majors,' who have their own distribution system. Marketers deliver to rural areas. We take the 'leftovers.' In terms of diesel, we deliver wherever it's consumed. Main routes are I-90 East, East of the Cascades, and the I-5 corridor in Southwestern Washington, just North of Portland."

6. *What is your delivery cycle for each delivery location (daily, weekly, etc)?*

   "It depends. We make 50-70 deliveries a day. Some delivery locations are served daily, others are only served once a week."

7. *What is the capacity of your vehicle's tanks?*

   "Our trucks carry 11,000 gallons of gasoline, and 9,800 gallons of diesel. Each truck has 5 compartments for different grades / varieties of product."

8. *What volume of diesel do you deliver during each visit (either in truckloads or volume of diesel)?*

[See above for truck capacity. Wilcox delivers full loads.] Side note regarding emergencies: "In an emergency situation, we make cardlocks a priority and we use them. We deliver to about 20-25 cardlocks in the CFN network, and 5-10 in the Pacific Pride network."

9. *What is the capacity of the storage tanks at each of your destinations?*

"Cardlocks store 12,000 gallons of gas and diesel and we usually deliver 'just in time.' Bulk plants, which serve agricultural communities, have 20,000 gallon storage tanks. Usually 2 diesel tanks – one on road diesel and one off-road disel – and 3 gasoline tanks, storing three grades of gasoline. The Longview bulk plant has a million gallons of storage, but volume varies a great deal depending on price and demand."

10. *Do you have an information management system that could provide us with this information for the last year?*

"We don't have that kind of information management system. We know storage tank sizes by customer, but no volume tracking. We also have some bulk plant information for insurance reasons, but no real management system."

11. *Is each destination always served by the same origin? Why or why not?*

"90% of the time, yes." Note: On occasions where the rack price is significantly less expensive at one terminal vs. another, Wilcox may load at the less expensive origin.

APPENDIX C: OTHER INFORMATION SOURCES

Energy Information Agency
State energy profile: http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=WA.

State profile includes a list of Washington's five refineries, oil and natural gas pipelines, average petroleum prices and consumption data, and list of oil import stations.

"Number and Capacity of Operable Petroleum Refineries by PAD District and State as of January 1st, 2006."

U.S. Army Corps of Engineers
"Waterbourne Commerce of the United States," 2006. Report on the amount of inbound / outbound petroleum products in Washington State ports (in short tonnes). Does not include origin or destination.

Washington State Department of Community, Trade, and Economic Development (CTED)
"A Primer on Gasoline Prices in Washington State," 2004.

British Petroleum
2007 Annual Report

Conoco Phillips
2007 Annual Report

Washington Research Council
"The Economic Contribution of Washington State's Petroleum Refining Industry in 2005," January 12, 2007.

Washington State Fuel Tax Division
Provided a list of diesel terminal racks in Washington, Oregon, and California.

IFC International
"Review of Pipeline Utility Corridor Capacity and Distribution for Petroleum Fuels, Natural Gas and Biofuels in Southwest Washington," ICF International, 2007. Report on pipeline corridor capacity and petroleum, natural gas, and bio-fuel distribution in SW Washington.

Inbound, waterborne crude flows from Canada (EIA DATA);

List of imported crude and crude products from Canada.

List of other contacts, including:

Name	Role	Office Phone
Mark Anderson	CTED (Washington State gov't)	360-725-3117

Pam Brady	BP/Olympic	425-981-2506
Rob Mathers	KinderMorgan	503-220-1258
Keith Leffler	U of W	(206) 543-5795
Frank Holmes	WSPA	360-352-4506
Charlie Brown	Wash oil Marketers	253-906-6685
Tyler Caruso	Crowley Marine	206-332-8085
William Kidd	BP - Public Relations	360-303-5349
Michael Abendhoff	BP - Public Relations	360-371-1519

Note that while some catastrophic interruption in refining capacity is not unlikely, it may be useful to consider another interruption – the possibility that changing demand patterns make it unprofitable for a major oil company to maintain their refining operation in Washington State. O'Connor supposed that a major oil company wouldn't necessarily hesitate to shut down a refinery that isn't yielding sufficient revenues, even though the state might suffer as a result.

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Washington State Petroleum Association

Called once, received no reply.

Cherry Point Refinery

Estimate of Cherry Point Refinery output by product type; estimated that in the event of a diesel shortage, they could produce another 5,000 barrels of diesel a day by adding jet fuel to existing diesel stock.

APPENDIX D: STAKEHOLDER MEETING

In order to support customer use of the GIS freight tool, this research project will identify deliverables that meet the needs of a broad range of transportation planners in the state. In an effort to better understand user requirements, the researchers held a meeting to discuss current needs for statewide freight modeling. The meeting included over 22 model users, representing several Metropolitan Planning Organizations, other regional transportation planning organizations, the Ports of Seattle and Tacoma, the Washington State Department of Transportation (WSDOT) and the Washington State Potato Commission.

The potential users agreed that the statewide freight model's primary use is would be to help them evaluate infrastructure investment alternatives and prioritize investment choices.

The users noted that other efforts have been made in the past to build a statewide transportation model, although not a freight model, and although a model was built it wasn't adopted at a state level. The reasons for failure included lack of executive level buy-in due to complexity and high cost. The participants suggested various ownership structures for the freight model, and agreed that they would like to be able to run the model themselves.

The group mentioned several models and datasets that are in use including models used by other states that could be considered when finalizing the economic impact analysis.

The group also agreed that all modeling efforts are currently limited by a lack of good commodity flow information for the state. The group was very supportive of data collection efforts, particularly prior to any statewide modeling effort that might be undertaken. The data needs to provide corridor-specific commodity flow information, and associate that information with industry sectors.

Similarly, any modeling effort should provide results disaggregated by industry. It would need to capture time of day effects from congestion, and seasonal differences in commodity flows. The model should capture both out-of-state markets and generators, and intrastate flows. The model should include the highway system, as well as important connectors and arterials. The group also made it clear that the model should have a GIS-based platform. The model should focus on flows between regions, given that some MPOs currently have traffic demand models.

Attendees:

1. Anne Goodchild, University of Washington
2. Hugh Conroy, Whatcom Council of Governments
3. Li Leung, University of Washington
4. Nick Manzaro, Wenatchee Valley Transportation Council
5. Alon Bassok, Puget Sound Regional Council (PRSC)
6. Eric Jessup, Washington State University
7. Glenn Miles, Spokane Regional Transportation Commission
8. Mark Harrington, Vancouver MPO (SWRTC)
9. Faris Almemar, Washington State Department of Transportation
10. Doug Brodin, WSDOT Research Office
11. Dale Tabat, WSDOT
12. Dave Honsinger, WSDOT
13. Elizabeth Stratton, WSDOT
14. Kumiko Izawa, WSDOT
15. Maren Outwater, PSRC
16. Ruth Decker, WSDOT
17. Anna Soderstrom, Port of Tacoma
18. Katy Brooks , Port of Vancouver
19. Matt Harris, Washington State Potato Commission
20. George Xu, WSDOT
21. Mark Rohwer, WSDOT
22. Sean Ardussi, PSRC
23. Todd Carlson, WSDOT