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Washington State Freight System Resiliency

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ABSTRACT

The economic viability and well-being of Washington State is significantly influenced by the freight transportation system serving the region. An increased understanding of the vulnerability of this freight system to natural disasters, weather, terrorist acts, work stoppages and other potential freight transportation disruptions will provide the State with the information necessary to assess the resiliency of the transportation system, and provide policy makers with the information required to improve it. This research project will: a) Identify a set of threats or categories of threats to be analyzed. b) Assess the likelihood of each event occurring within certain time horizons. c) With the threats and their probabilities, analyze the resiliency of the Washington transportation system. This will include 1) identifying the most valuable and least valuable components, both infrastructure and operational characteristics, of the transportation system with respect to moving freight, 2) identify the most likely events and the impact of those events, and 3) develop strategies for making WSDOT investments that would support improvements in the resiliency of the transportation system. Deliverables may include the following: i. Identification of the most likely events and failures ii. Identification of the weak points in the transportation system iii. Identification of improvements that will have the largest benefits in terms of the state's ability to move freight when faced with a transportation system failure iv. Identification of the most important elements of the transportation system in terms of the state's ability to move goods v. Provide suggestions as to how WSDOT investments can best improve the resiliency of the transportation system. The outcome of this research effort will help shape and guide transportation policy and infrastructure investment decisions in the future.

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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 prevent long-term negative economic consequences to state and regional economies. We set out in this project to develop an empirical approach and methodology that can be used to estimate the vulnerability of different industry sectors within the Washington State economy to disruptions in the transportation system. More specifically we proposed to:

1) Develop an empirical approach and methodology that can be used to estimate vulnerability of different economic industry sectors to disruptions to the transportation system, and

2) Provide results from applications of this methodology to examples in Washington State. Our original proposal indicated we would consider 3 to 5 examples, but this was reduced to 2 upon identification of the challenges of data collection. These are the fuel delivery system and the potato industry.

Our research has been structured in five work streams:

1) Interviews with transportation providers regarding their current responses to transportation disruptions. This was necessary to understand the current responses to resilience, and the cost implications.

2) An extensive literature review on the topic of resilience and a framework for evaluating the resilience of the transportation system.

3) Development of a comprehensive multi-modal state freight transportation network in a GIS framework.

4) Identification and execution of two case studies. We will evaluate the impact of a 1 day closure of I-90 at Snowqualamie Pass on the Washington potato industry, and a disruption to the Washington state fuel supply system. Work on this task is not complete.

5) Interviews with stakeholders regarding the applications of and value in a statewide freight model.

This work completed to date is summarized in this document. In addition, research from the first work stream is currently in preparation for submission to the Journal of Business Logistics. The research from work stream 2 was accepted for publication and presentation at the 88th Annual Meeting of the Transportation Research Board. The GIS network has been created and is being used for the execution of the two case studies. The results from these 5 work streams are included in this document. Through this work we have laid a foundation for the development of a methodology for estimating the economic significance each component of the freight transportation system. These work streams relate to the tasks set out in our original proposal as follows:

Executed work stream	Original proposal task
Work stream 2	Task 1: Identify categories of transportation system failure under consideration.
Work stream 3	Task 2: Develop a statewide freight flow map
Work streams 1, 2, 3, and 4	Task 3: Develop an improved methodology
Work stream 4	Task 4: Develop and execute case study scenarios
Work stream 5	Task 5 Synthesize results from the what-if scenarios

Our research in this area is ongoing and will continue beyond that reported in this report. This work has been matched by funding from WSDOT that was provided over the 2 year period from July 2007 through July 2009. The funding from TransNow as provided originally for the period July 2007 through July 2008. The final scope of work for the matching WSDOT funding was agreed on January 23, 2008. Given this delay in initiating the work, a six month extension was granted from TransNow. Final execution of the case studies and synthesis of these results has not been completed, but will be completed prior to the completion of the WSDOT project in June of 2009.

The rest of this report summarizes the findings from the completed work to date. As noted above, work on the 2 case studies is not yet complete, but will be completed by June 2009, the end date of WSDOT funding. The next section defines resilience in the context of the freight transportation system, and provides a review of the related resilience literature. Section 3 describes current supply chain responses to disruptions. Section 4 describes the multi-model freight transportation network that has been developed for the state. Section 5 describes the case studies currently under development. Section 6 describes the results of a statewide freight model stakeholder meeting held to discuss the uses and performance characteristics of a statewide freight model which could be used to address many state needs, including, understanding the resilience of the current freight transportation system. We conclude the report with section 7.

2. Defining Resilience of the Freight Transportation System

2.1. Introduction

The ability for the system to absorb the impacts from a disruption and continue moving traffic in an uninhibited manner is one definition of freight transportation system resilience. This simple definition is the derivation of a dictionary definition of resilience, which defines resilience as “an ability to recover from or adjust easily to misfortune or change (Bruneau et al, 2003). From this simple definition, resilience is tied to elements of flexibility, elasticity, and an ability to recover after some disturbance. This everyday interpretation of resilience is an effective guiding principle; however, defining resilience in order to measure system performance, the concept must be deconstructed into meaningfully measureable components. This section will provide a definition of resilience for freight transportation systems that is the result of the extensive literature review on resilience and includes the three dimensions of the freight transportation system, the physical infrastructure, users, and the organizational dimensions. 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 and travel including the information infrastructure embedded in these facilities or located in fixed locations near them. The users include all organizations and individuals that use the infrastructure to transport people and goods. The managing organization is the unit that oversees the construction, maintenance, and performance of the infrastructure. The focus of this paper is on the transportation of goods given the emerging interest in freight transportation system planning. It must also be recognized that the decisions of users or business entities do affect the overall system resilience through their actions.

Resilience is a commonly used, however ill-defined term in the context of freight transportation systems. By no regard 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, State Departments of Transportation (DOTs), and freight transportation systems. It has become a familiar part of the contemporary discussion of freight transportation systems, yet lacks a widely accepted, standardized definition and agreed upon measures. Definitions of resilience are somewhat clearer within the business supply chain context, but this is not true of freight transportation system resilience in general (Godschalk, 2003),(Miles and Chang, 2006). It is important to place emphasis on the resilience of the freight transportation system, which includes the physical and information infrastructure, infrastructure users, and infrastructure managers. A consistent framework and definition for resilience will help guide investments and behaviors to create a more resilient freight transportation system. A resilient freight transportation system is critical in a time when the economic system is highly dependent on a reliable freight transportation system.

To date, assessing structural vulnerabilities of infrastructure has been the primary method of measuring infrastructure performance in light of resilience of transportation systems (Murray-Tuite and Mahmassani, 2004), (Rowshan, Smith, et al, 2004), (Hood, Olivam Slocter, Howard, and Albright, 2003). Beyond assessing infrastructure vulnerabilities, activity around freight transportation system resilience is also documented by efforts of State DOTs and metropolitan planning organizations in order to enhance their access to data, encourage more detailed and comprehensive data collection, and subsequently construct accurate multimodal freight models (Xiong, 1990). Resilience hints at the sense of responsibility for the freight transportation systems' managing organization to take a more active role to understand the intricate relationship between freight transportation, system infrastructure, and economic activity. A clearly structured definition of resilience will support State DOTs' emerging interest in freight transportation system resilience.

2.2 Related Applications of Resilience

2.2.1 Supply Chains

Literature related to resilience and freight transportation systems has been addressed in the context of supply chains through the idea of "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" that is "used to reduce the occurrence or mitigate the effects of disruptions, allowing a supply chain to maintain or return to normal operating conditions" (Pitera, 2008). Pitera provides a framework to assess the resilience of enterprises' supply chains, which 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, 2008). Her work on corporate resilience strategies provides some insight into the resilience strategies of freight transportation system users, though not directly addressed here, is of major importance to overall freight transportation system resilience. For instance, the decision of a trucking company to cancel a route in their shipment plan equates to less trucks on the road, less demand for roadway capacity, which alters the state of the system and influences the impact of management decisions on the network's performance. Disseminating information regarding system performance, therefore, improves system performance.

2.2.2 Enterprises

Resilience has also been studied in the organizational, or enterprise, context where it is commonly, however not solely, attributed to the presence and engagement of good communication within and between enterprises, or private business organizations. In the example of private businesses, good communication strategies that are diverse, flexible, and adaptable support the overall corporate resilience (Sheffi, 2005). Pitera further reinforces the contributions of good communication strategies to corporate resilience as a strategy for disseminating timely and accurate information (Pitera, 2008). Beyond good communication, Sheffi provides qualitative analyses of select companies that highlight strategies to build flexibility into private organizations to enhance their resilience. For example, informal networks based on personal relationships, leadership at all levels, distributed power, and a general obsession with results characterizes Dell Computers, at the organizational level to support its ability to be flexible and absorb unanticipated disruptions in its supply chains (Sheffi, 2005).

2.2.3 Infrastructure

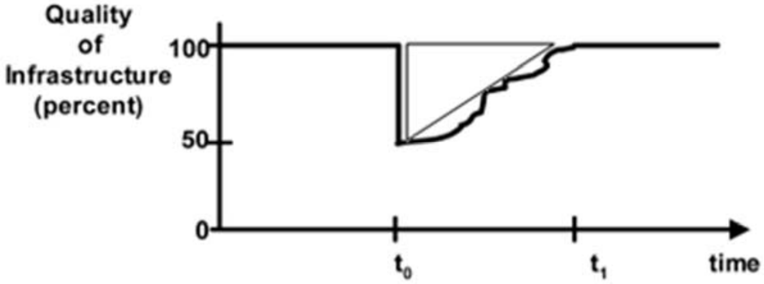
In addition to organizational resilience, studies have also related resilience to the physical infrastructure. Here, resilience is defined as the timely ability of the infrastructure to absorb surges in traffic demand and recover from disruptions.

Transportation infrastructure resilience has primarily been measured in a general transportation system context to understand vulnerabilities in transportation networks and therefore guide investment in transportation infrastructure to fortify against disruptions and improve recovery after a major natural or man-induced disaster (BTS, 1998), (Chang, Ericson, and Pearce, 2003). (Chang and Nojima, 2001), Morlok and Chang, 2004), (Litman, 2008b). Methods that have emerged center on assessing the availability of alternate routing, the reduction in total delay, the adaptive use of high occupancy vehicle lanes and the ability to transfer travel demand to other non-single occupancy vehicle modes to free highway and roadway capacity to maintain freight mobility (BTS, 1998).

2.2.4 Disaster Research

Disaster research has also touched upon the broad intersection of resilience and freight transportation. For more than seven years, researchers with the Multidisciplinary Center for Earthquake Engineering Research (MCEER) have focused attention on conceptualizing and measuring disaster resilience. They 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). Resilience in disaster research therefore 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 for recovery. Disaster research generally falls into four defined 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). A specific resilience strategy could therefore be targeted to reduce the probabilities of failure, the consequences of failure, or the time for recovery.

The concept of a “resilience triangle,” which “represents the loss of functionality from damage and disruption” emerges from disaster research (Tierney and Bruneau, 2007). The resilience triangle helps visualize the magnitude of the impacts of a disruption on the infrastructure. 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 capture the probability of the disruption occurring. Figure 1 shows the resilience triangle for a 50% loss in infrastructure functionality. The smaller the triangle is, the more resilient the system. Actions, behaviors, and properties of social units, organizations, and networks all contribute to reducing the area of the resilience triangle.



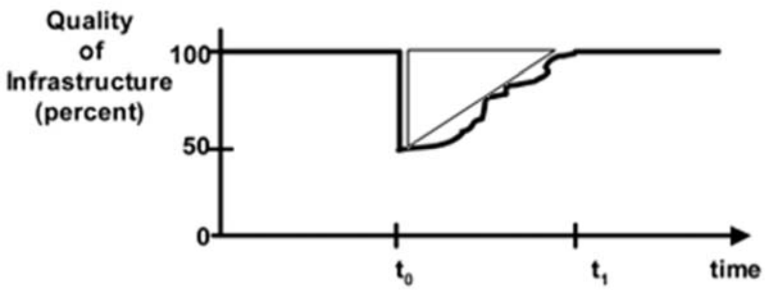


Figure 1 Resilience Triangle (Tierney and Bruneau, 2007).

Bruneau, a well published and frequently cited author in seismic disaster and community resilience research defines resilience as “the ability of social units (e.g. organizations, communities) 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 (Bruneau et al, 2003). They suggest a 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 analytical difference between resilience of a system prior to, during, and after a disruption (Bruneau et al, 2003). Furthermore, resilience suggests concurrence of “apparent opposites such as redundancy and efficiency, diversity and interdependence, strength and flexibility, autonomy and collaboration, and planning and adaptability” to explicate the complex nature of resilience and highlight the potential for confusion around current applications of resilience (Godschalk, 2003). In constructing a definition for freight transportation system resilience, the nuance offered by disaster research is a reminder that a specific combination of strategies can promote resilience yet the same strategies may be in competition if engaged independently and in isolation.

2.2.5 Regional Input/Output Models of Economic Activity

Input/Output models are used to model regional economic productivity. The aggregate approach to quantifying the economic consequences of disruptions to the transportation system is to tie these regional input/output models to the transportation infrastructure. Here we describe several regional input/output models.

Anselin, Luc, and Moss Madden (1990) provide a nice summary of regional models. Traditionally, input-output models have been used to understand economic activity, first at the national level and then adapted for regional economic analyses (also Bourque, John, and Cox). Currently, state-level commodity flows are the finest level of quality data available. Studies of economic activity of regions focus on economic activity within industry sectors, and look at indices for the economic ‘health’ of regions. The indices rely on population, productivity (employment), and income as indicators of that health. They have yet to incorporate transportation as a factor in calculations of economic activity.

There are, however, a few examples of regional input/output models that have incorporated transportation to a limited degree. For example, Hirsch (1967) describes a regional I/O model of the urban government to determine allocation of government expenditures for government planning purposes. This includes the ‘Street services sector' (1 of 5 sectors in the urban government I/O model) which includes traffic and transit activities of the urban government; related to economic activity of region, population density, sprawl/distance between work and residences. This includes roads & transport, street cleaning & lighting, parking & street patrol, vehicle licensing & regulation, etc. Regional Economic Modeling Inc (REMI), uses four types of models Input-Output, General Equilibrium, Econometric, and Economic Geography, however, complete details of the model cannot be known due to the proprietary nature of the company. It does not distribute modeling details.

2.2.6 Planning Models

We present one example of a regional simulation that connects transportation activity to economic activity, created by Waddell titled UrbanSim. UrbanSim is open source and so complete modeling details are known. UrbanSim looks at the economic impact of transportation investments in terms of land use. UrbanSim does tie together land use values and transportation infrastructure improvements despite not directly mapping economic values to infrastructure. UrbanSim ties together traditionally separate land use simulation and transportation demand models to illuminate the land use-transportation relationship. The UrbanSim model can capture the long-term landuse changes that might be induced by transportation infrastructure changes, or the impact of landuse changes on demand for transportation in the long term.

Table 1 Concept Definitions for Resilience and the Freight Transportation System

Concept	Definition
Resilience	the "ability to recover from or adjust easily to misfortune or change" (Rice and Caniato, 2003).
Physical Infrastructure	the system of network of nodes and links (e.g. port facilities, distribution centers, warehouses, intermodal yards, bridges, rail lines, and roadways) sensors, and information technology infrastructure that support freight transportation and travel.
Managing Organization	the unit that oversees the construction, maintenance, and performance of the freight transportation physical infrastructure. This includes the management, utilization, and dissemination of roadway data.
System Users	business enterprises that move goods on the transportation infrastructure and utilize roadway information.

2.2.7 Vulnerability

It is important to consider the relationship between resilience and vulnerability. Berdica (2007) aims to conceptualize the vulnerability of the road transportation system. She discusses the concept of vulnerability and situates it within a range of related concepts/disciplines (robustness, resilience, redundancy). Traditionally discussing vulnerability takes a 'safety point of view', Berdica argues for assessing vulnerability 'as a problem of an insufficient level of service'. Berdica suggests reliability theory can be used for the evaluation of these indices, provided that levels for the unacceptable/inadequate are set first. By choosing this wider interpretation, reliability can be regarded as a complement of vulnerability, where reliability means adequate serviceability under the operating conditions encountered during a given time period. Berdica presents different types of reliability used in older vulnerability assessments - time travel, terminal, capacity and newer vulnerability assessments (include travel demand satisfaction reliability, encountered reliability). She also discusses limitations of current vulnerability assessments.

2.4. Defining Resilience for the Freight Transportation System

A structured definition of freight transportation system resilience recognizes that resilience of the freight transportation system falls on the physical infrastructure and managing organization dimensions. We define freight transportation system resilience as the ability for the system to absorb the consequences of disruptions, to reduce the impacts of disruptions, and maintain freight mobility. Table 1 shows a definition of resilience from Rice and Caniato, 2003. Notice this definition does not include the ability to reduce the impact of disruptions, however, this is a key element of our definition. This is an important element of transportation system resilience, as it is these mitigation efforts, that can be undertaken by a managing organization. Resilience hints at the sense of responsibility for the managing organization that is associated with recovery and readiness. Part of the system's ability to absorb shocks and disruptions is related to both the capacity for resilience in the physical infrastructure as well as the capacity of the managing organization to respond, engage resources, and prioritize the use of limited infrastructure. There is an intricate relationship between the physical infrastructure and the managing organization because the nature of recovery from major disasters includes, for instance, long term planning timeframes dictated by the repair or replacement of debilitated infrastructure and the dependency of many sectors of a community on transportation infrastructure and the freight transportation system to distribute goods to market, provide employment, and support the conveniences of modern life.

2.4.1 Resilience at the Infrastructure Dimension

Traditionally, transportation systems have been identified by their infrastructure components, although there are other major dimensions that comprise the functioning of a transportation system such as the users of that system and the managing organization. For a freight transportation system, the physical infrastructure is a fundamental piece of the freight transportation system. It provides the network on which goods travel and contribute to economic activity. Resilience on this dimension is the ability of the network, given its capacity to supply lane miles, to facilitate the movement of goods under capacity-constrained conditions due to a disruption such as the inaccessibility of road or a bridge. Additionally, the infrastructure itself contains the capacity for resilience in the design and quality of structures of that infrastructure. Resilience on this dimension is achieved through sufficient infrastructure and transportation network robustness (Bruneau et al, 2003). Given its static nature, the innate characteristics of infrastructure offers one level of resilience; however, it can contribute to greater freight transportation system resilience when its capacity is properly managed.

2.4.2 Resilience at the Managing Organization Dimension

Infrastructure management occurs within the organizational dimension. Awareness of properties of infrastructure resilience provides the managing organization, namely a State DOT, information about the system resources. This information and awareness fosters the DOT's ability to effectively manage, allocate, and deploy resources when preparing for and responding to disruptions. The ability for the managing organization to prepare for and respond to disruptions in a timely manner is an indirect measure of the freight transportation system's resilience.

One organizational resilience strategy includes effective communication within the managing organization and between the managing organization and other organizations involved in transportation system management (e.g. the highway patrol). 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 the overall freight transportation system's resilience. The managing organization's resilience contributes to the overall resilience of the freight transportation system, which suggests that properties of resilience at the organizational level should, therefore, include properties that can quantify actions and behaviors that promote information sharing, support quality and timeliness of information, and the successful external dissemination of information. In other words, rapidity of the managing organization, and "the capacity to meet priorities and achieve goals in a timely manner in order to contain losses," is the desired outcome of organizational resilience (Brunueau et al, 2003).

The performance of both these levels of the freight transportation system will greatly affect the freight transportation system's resilience; therefore, a framework for defining freight transportation system resilience offers the opportunity to begin a systematic assessment of system resilience to guide freight transportation systems planning, operations management, infrastructure investments, and program investments.

2.4.3 Resilience at the User Dimension

Although freight transportation system users are not generally responsible for promoting the system's resilience, individual enterprises' actions can impact system performance, and therefore a system's ability to move goods and return to a satisfactory level of performance after a disruption. For an enterprise to successfully and efficiently move goods, government agencies must provide and manage infrastructure, and, in return, for government agencies to provide satisfactory service on that infrastructure, enterprises must behave in a way that supports system function. For example, trucks must secure open loads, and observe height restrictions as a means of avoiding disruptions. Additionally, during congested periods, system performance can improve if vehicles re-route or re-schedule. Interactions between individual enterprises and the system's managing organization are necessary for either to achieve resilience. Governmental agency policies and the status of the physical infrastructure are precursors to the resilience of enterprises. Often, a government's response to disruptions can have a greater impact on the enterprise than the disruption itself. With regards to both large-scale and daily disruptions, the policies of the federal, state and local governments impact an enterprise's ability to move goods. These policies include federal policies such as the Customs-Trade Partnership against Terrorism (C-TPAT) and the Container Security Initiative (CSI), and local policies such as hazard mitigation plans (Rice and Caniato, 2003). To be prepared for a number of potential disruption scenarios, enterprises that have the ability to disseminate information quickly, delay decision making, postpone shipments, and alter the path of the supply chain by calling on alternate suppliers facilitate the resilience of the freight transportation system. Freight transportation system resilience is a product of the dynamic interaction between organizational entities, user enterprises, and the physical infrastructure. The effectiveness of resilience at the user dimension contributes to overall system resilience to the extent that system users and the system managers are well connected with dependable and trustworthy channels of communication and fortified relationships prior to the onset of a disruption.

Table 2 Concept Definitions for Freight Transportation System 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.
Managing Organization Resilience	"the capacity to meet priorities and achieve goals in a timely and efficient manner in order to contain losses" (Bruneau et al, 2003).
Enterprise Resilience	the ability of an enterprise to move goods in a timely and efficient manner in the face of infrastructure disruption.
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. 4.4. Resilience Pre-, During, and Post-Disruption

Delineating the temporal location of resilience into pre-, during, post-disruption time periods allows planners and decision makers to understand the impact of specific resilience strategies on overall freight transportation system resilience. Drawing from the reviewed literature on disaster research, four analytical categories provide the temporal framework in relation to the disruption: mitigation, preparedness, response, and recovery. The properties of resilience can be categorized by the time period during which they support specific resilience strategies that most directly contribute to the freight transportation system's ability to absorb shocks and reduce the consequences of disruptions.

Many actions and behaviors that promote resilience are most applicable to pre-disruption strategies or mitigation efforts. Mitigation describes actions and behaviors that are taken prior to any disruption that help curb the impact of the consequences from the disruption (Haddow and Bullock, 2004). Examples of mitigation efforts in the infrastructure dimension include the seismic retrofitting of bridges and overpasses or the investment in retaining walls, whereas at the organizational dimension, fortification strategies include the prioritization of freight system users in anticipation of limited infrastructure capacity and establishing processes for efficient information sharing with freight users so they can independently make appropriate decisions about how to best use available infrastructure capacity. The Washington State DOT is one of the few states to pursue study of freight system resilience planning and has recently published their report on resilience planning (MIT, 2008). The actions and behaviors taken by users and organizations during (i.e. response) and after a disruption (i.e. recovery) will also impact overall freight transportation system resilience. Typically these are actions or behaviors engaged by the organization or users, as infrastructure changes take longer to implement. Rapid dissemination of information regarding the disruption and reallocation of repair crews to address the disruption are examples of actions that can be taken during and after the disruption to improve resilience (Brown and Baigel, 2007), (Oakland Tribune, 2008). To choose the appropriate resilience strategy, a State DOT must evaluate the effectiveness of resilience strategies to impact capacity reductions or aid in the reconstruction and resumption of major infrastructure damages.

2.5. Properties of Resilience

Freight transportation system resilience has been defined and discussed by the actions and behaviors taken by users and organizations that may increase system resilience. These actions or behaviors increase the affect on properties of resilience, as defined below. It is these properties that, under various disruption scenarios, allow the freight transportation system to be more resilient. Users, managing organizations, and infrastructure can have these properties.

In terms of resilience for complex systems, Foster offers a starting point for identifying the essential properties. He identifies thirty-one properties of resilience for complex systems from which metrics may eventually be developed (Oakland Tribune, 2008). Specific to the freight transportation system, six properties of resilience are drawn from the reviewed literature: redundancy, autonomy of components, collaboration, efficiency, adaptability, and interdependence (Chang, Ericson, and Pearce, 2003), (Chang and Nojima, 2001), (Morlok and Chang, 2004), (Litman, 2008a), and (Murray-Tuite, 2006). These six properties of resilience were consistently mentioned across the transportation literature as critical properties and support a freight transportation system with the ability to absorb shocks and maintain adequate freight flows. Of Foster's thirty-one properties, these correspond to the capacity to satisfy several goals and objectives, diversity of components, functional redundancy, rapidity, efficiency, and incremental operation. Defining these properties of freight transportation system resilience establishes the detail required for a meaningful definition of resilience. A cursory introduction of these six properties' definitions will shed light on their applicability to freight transportation system resilience.

Table 3 Concept Definitions for Properties of Freight Transportation System 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 a routine and robust communication system.
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.
Property of Resilience	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 (Godschalk, 2003).

The properties of resilience in a transportation system here presented are by no means comprehensive or exhaustive; however, there is consistency within the literature reviewed to support naming redundancy, autonomy of components, collaboration, efficiency, adaptability, and interdependence as the most direct properties of a framework for defining freight transportation resilience. These properties can contribute to the overall ability of the freight transportation system to recover from disruptions whether exhibited at the infrastructure, organizational, or user dimension.

The framework in Table 1 finds structure from the three dimensions of the freight transportation system, the physical infrastructure, the managing organization, and users. Properties of resilience are then attributed along these dimensions. The framework also defines the contribution of each property of resilience to the overall freight transportation system resilience.

Table 4 Six Properties of Resilience for the Freight Transportation System

Properties[a]	Examples of Applications of Resilience			Contribution to Freight Transportation System Resilience
	Physical Infrastructure Dimension[b]	Managing Organization Dimension[b]	User Dimension[b]	
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	Working partnership between federal, state, regional an d local public agencies to plan, construct and operate the full freight transportation network to optimize system use	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 miscommunications, spreads risk across groups Promotes network, versus local, freight system optimization and resiliency.
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 or for the capability to expand capacity without total facility reconstruction ; ability to assume diversity functions (e.g. adaptable-	Familiarity of roles and responsibilities across levels of the organization ; cross-trained employees ; leadership can be engaged at all levels. Defined roles and protocols during disruption and recovery phases.	Ability to postpone decision making & shipping ; build-to-order business model[e]	Promotes flexibility & system efficiency ; supports robustness

	use HOV lanes)			
INTERDEPENDENCE	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 Murray-Tuite, 2006.
[b]Examples of the property of resilience; not comprehensive or exhaustive.
[c]Further mentioned in Murray-Tuite, 2006.
[d]Further mentioned in Litman, 2008a.
[e]Sheffi, 2005.

It must be noted that the contribution to overall freight transportation system resilience of each of the six separate properties are not mutually exclusive. That is, resilience strategies that promote adaptability may also promote efficiency. Moreover, not only are the contributions to resilience overlapping, some properties may appear to be in conflict (e.g. autonomy of components and interdependence), hinting at the complexity of resilience. Although individual properties of resilience may independently contradict one another, resilience of complex systems, like the freight transportation system, is achieved through the tradeoff between resilience strategies that will highlight specific properties of resilience. The tradeoffs are a function of the type of system, the extent of the system under consideration, and the particular nature of the risks involved. It is, therefore difficult to suggest a specific course of action, applicable under all disruption situations to increase the resilience of the freight transportation system. Given the diverse application of resilience to specific systems and situations, a case by case method of analysis must be undertaken to identify the appropriate strategies to pursue along each dimension. It should also be noted that most freight transportation systems do not have a single decision-making body for whom resilience is a high priority. There are a number of recent studies that examine resilience strategies of individual enterprises and the conditions under which specific strategies contribute to resilience. However, given the widely used, yet vague definition of resilience, the ability of the system to absorb shocks and reduce the consequences of disruption, the structured definition of resilience developed in this paper establishes a starting point for future resilience measurements, assessment, and evaluation of freight transportation system performance.

2.6. Summary

This section summarizes a broad literature review on system resilience. In addition, we provide a definition of freight transportation system resilience that captures the interactions between managing organizations, the infrastructure, and users. This is critical considering the freight transportation system exists to support economic activity and production. The resilience triangle provides a tool for visualizing the temporal aspects of the consequences of a disruption. We also offer a list of properties of freight transportation system resilience that can contribute to the overall ability of the freight transportation system to better respond and recover from disruptions at the managing organization, infrastructure, or user dimensions.

Combined, these concepts provide a framework through which a more structured conversation about freight transportation resilience can take place. This framework can assist in strategic planning discussions, investment decisions and resource allocation to enhance freight transportation system resilience and performance. The exact strategies undertaken by a managing organization will depend on the risks faced, the existing state of the system, the available resources, and the extent of the system under consideration. Being able to identify and then understand the component properties of the nebulous concept of resilience and the association of those properties across the three dimensions of the freight transportation system, State DOTs will be well positioned to meet their responsibility of managing freight mobility and supporting regional economic activity.

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 11, 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.

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 when considering 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, the introduction of 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 to cope with disruptions and a minor disruption has the potential of shutting down the entire supply chain (Sheffi 2005). Enterprises which operate Just-in-Time (JIT), where supplies or components arrive at almost the exact time they are needed instead of being held in inventory, are vulnerable to transportation disruptions where 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, or 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) is a comprehensive overview of the changing focus of supply chains in a post-September 11 world. Sheffi explains the importance of resiliency, explores potential vulnerabilities in supply chains, and introduces 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) examines 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 yields lessons regarding preparation and reactions to future disruptions and provides recommendations to strengthen supply chains, reduce disruptions, and maximize resilience in the future. Christopher and Peck (2004) examine supply chain risks and suggest 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 which embraces the risk management concept.

3.2.2 Supply and Demand Disruptions

Snyder and Shen (2006) discuss managing disruptions to multi-location supply chain systems, and suggest 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) develop 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) looks at supply uncertainty 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 to identify sources of, assess, and mitigate external risk, such as natural disasters, economic disruptions or terrorist activity. Rice and Caniato (2003) focus on disruptions at all levels of the supply chain due to terrorist activities and governmental responses due to these potential threats. Through a series of interviews with firms in the United States, their research details corporate risk assessment and corporate response to recent terror activities, namely September 11th. Sarathy (2006) examines 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) discusses the importance of organizational culture in resilient supply chains. Benson's study consists of corporate interviews focusing on work infrastructure and practices, human resources practices, education, communication, and measurement systems to examine enterprise policies and how they impact security and resiliency of supply chains.

3.2.5 Network Structure

Focusing on network structure and the impact of disruption on costs and flow over the network, Latora and Marchiori (2005) discuss a method of finding the critical components of an infrastructure network. These nodes and the 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) discuss models for planning supply chain networks which are resilient to disruption. These models attempt to allow supply chain infrastructure to be designed to operate efficiently and at low-cost both during times of normal and disrupted operations.

The research presented here describes how enterprises are currently 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. We consider how these strategies improve resilience, and how these strategies are related to the enterprise's experience with risk management. 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 Data and Research Methodology

3.3.1 Data Sources

Data regarding resiliency strategies used was 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 take 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 5.

Table 5 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 operate in multiple industry sectors with the dominate sector listed in Table 5. 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 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, which were not necessarily asked of each interviewee. This research focused on an enterprise's perception of their resiliency in addition to their 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 provided valuable insight, such as into their 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 provides insight into the resiliency strategies being used by interviewed enterprises but does not provide a basis to make universal conclusions on supply chain resiliency. This research does 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 focuses 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

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 focuses on resiliency within the goods movement segment of the supply chain.

Disruption

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

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 is 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

3.5.1 Introduction

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, fifteen resiliency strategies were identified. These strategies were both directly and indirectly identified by enterprises. If a enterprise did not report a strategy it can be assumed that (1) the enterprise does not practice the strategy, (2) the enterprise does employ the strategy but does not find it significant to their resiliency efforts, or (3) the enterprise does employ the strategy but fails to mention its use because it has become commonplace within supply chain operations.

Strategies are categorized as being either enablers or tactics. Enablers do not directly improve resiliency, but instead facilitate the success of tactics. They enable or encourage resiliency. The majority of strategies are characterized as tactics, as they are tactical decisions. The resiliency strategies identified within the interview process are listed in Table 6.

Table 6 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

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

3.5.2 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.

Relationships

Definition: An enterprise develops and maintains relationships with suppliers, carriers, and customers, with 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 impact a supply chain and mitigate the impacts of a disruption that does have an effect on a supply chain. Beyond having a strong relationship, an action must be taken to avoid or mitigate the disruption, which often comes 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.

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 regarding 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 time sensitive 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.

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 regarding disruption between parties within the supply chain. Having the 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.

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 experienced with/conditioned for disruptions. Like the previous enablers, flexible culture encourages activities which reduce exposure to or mitigate the impact of disruptions.

3.5.3 Tactics

Tactics are typically part of an enterprises 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.

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 drawing on out-of-region carriers, to reduce the effects of a disruption which affects primary carriers.

C-TPAT Certification

Definition: An enterprise is Customs-Trade Partnership Against Terrorism (C-TPAT) certified with 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: Based on 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 priority to get freight out of the ports as soon as possible after the event.

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 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 within close proximity to several distribution centers and there is available inventory, 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.

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 their own resiliency in order to improve overall supply chain resiliency, this strategy is successful and allows an enterprise to avoid or mitigate the effects of disruptions. The supplier and the enterprise are often both vulnerable to the same risks.

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, there can be a shift to an accelerated mode of transportation to make up for time lost in early segments of the supply chain, or a second shipment sent via accelerated mode.

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 are likely to reach their destination on time. While using multiple ports and/or carriers can improve resiliency, it also results in increased risks. When including additional ports to a supply chain, an enterprise takes on the extra risks associated with importing into that port, which may be distinct from risks at previous ports and therefore must also be accounted for in additional resiliency planning.

Employees Overseas

Definition: An enterprise locates employees overseas, in locations which 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 they are in closer contact with the suppliers/carriers and while still reporting directly to the enterprise. There is also a presumed benefit of local knowledge that can be utilized by overseas employees.

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 facilitates improving resiliency through redundancy.

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 where congestion is minimal reduces the risk of disruption or delay due to congestion.

Sourcing of Components Domestically

Definition: An enterprise acquires components/goods from domestic suppliers instead of from suppliers overseas (where they may be cheaper) due to 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 which are critical to operations of an enterprise, such as a component which would stop a production line if not available or a product with no reasonable replacement.

Premium Transportation

Definition: An enterprise uses a more expensive mode of transportation assuming they offer a service which 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 there is a disruption which 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 prior to the disruption physically affecting 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 in made on an operational basis as events develop. Likewise, it is a strategic decision to allow for 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 through strategies such as flexible transportations where goods can be shipped ahead or behind schedule in order to avoid potential disruptions. Risk can also be spread geographically through strategies such as use of multiple ports, and spread through personnel in strategies such as employees overseas.

3.6.2 Relationship to Current Operating Environment

The enterprises interviewed fall into three general business sector categories: manufacturing, retail, and food/beverage. By examining strategies utilized by each enterprise, it is apparent that resiliency strategies are less likely to be linked to the specific nature of the business but more so 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 operating environment which the enterprise works within. 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 which are prone to disruptions, even those unrelated to transportation, develop a resilient supply chain and therefore are more resilient to transportation-related disruptions. Table 7 summarizes the strategies indicated by enterprises directly during interviews.

Table 7 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 are classified as retailers, and while all three make use of enablers, other strategies utilized vary widely. Within the retail sector there is a large diversity of businesses and business models, meaning each supply chain has different resiliency needs. The enterprises interviewed do not operate supply chains which are exceptionally lean or volatile. Instead, these enterprises understand, in the general sense, that resiliency can benefit a supply chain, and have chosen to explore how resiliency can best be implemented into their own supply chain to address their specific needs.

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

Enterprise E operates in the food and beverage business sector and primarily produces commodities that are 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 their 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 their 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 due to more overall time in transit. Enterprise E has developed a mature resiliency approach due to likelihood of disruption, the severe consequences of disruption, and high competition associated their supply chain and operations. The strategies employed by Enterprise E, such a sourcing many critical components domestically and making off-peak deliveries, display this maturity. While these strategies weren't initially implemented to improve transportation resiliency, they do improve an enterprise's ability to minimize or mitigate transportation disruptions.

Enterprise F also provides food products, but displays less resiliency maturity than Enterprise E due to previous lack of experience with disruptions. Having a domestic supply chain reduces the potential for disruption, and may be 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 their resiliency procedures. As a relative newcomer to the area of resiliency, Enterprise F is 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 believes their supply chain response improved due to the strategies in place. One can expect that as Enterprise F continues to explore and understand the importance of resiliency within their supply chain, the strategies they chose to implement will be similar those of Enterprise E. Enterprise F's actions align with previous research asserting 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, Enterprises H, J, and I, use similar strategies, such as use of information and technology, expedited freight, and premium transportation, but they do not employ these strategies solely for the sake of resiliency. Both Enterprise H and Enterprise I manufacture expensive products using a JIT strategy, meaning 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 like the transportation network. A JIT supply chain needs to actively increase resiliency and able to respond to delays in order to be successful. Given the size and value of the good produced by both these enterprises, the extra expenditures required to implement information technology systems and use expedited and premium freight are inconsequential to the costs of holding increased inventory and potential assembly delays. Enterprise J does not operate as a JIT supply chain but provides service to enterprises who value expedited service very highly. As with Enterprise H and Enterprise I, whose manufactured goods cost in the hundred thousand and hundred millions respectively, the cost of transportation is negligible when concerned to the cost of customers' delays of business due to delayed goods. Similar to Enterprise J, Enterprise G provides products to enterprises that operate JIT and therefore value high levels of service. Higher values 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 which operates with a JIT strategy can also be considered mature due to concerns 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 JIT, large manufacturing supply chain. Within these industries, transportation resiliency exists because of the enterprises' desire to reduce costs and their previous experience and response to disruptions.

3.6.3 Relationships between Strategies

Upon examination of strategies, it was evident that some strategies compliment, 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 are 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, it should be noted that not all of the strategies identified during the interviews can be implement at once by one enterprise.

3.7 Conclusions

This research was motivated by the continued increases in trade volumes, lengthening of supply chains, and increased focus on disruptions and resiliency within the supply chain community. As enterprises attempt to improve resiliency, it is important to understand their perception of the concept and the means by which they attempt to achieve resiliency. Through interviews it appears that while resiliency was in the field of vision of interviewees, the concept was not a supply chain priority. While resiliency can impact supply chain costs and efficiency, and enterprises often cited costs and efficiency as supply chain priorities, there appeared to be a disconnect between the impacts of resiliency and enterprise priorities. Resiliency, while acknowledged, was not part of most enterprises' daily language, or discussed using other terms such as reliability and consistency. Despite this, evidence of resiliency within enterprise supply chains, specifically the transportation component, was encountered.

With knowledge of the existing literature, a framework for consideration of resilience of the freight transportation system, and knowledge of current supply chain responses to transportation disruptions, we can proceed to identifying a platform for use in analyzing the resilience of the regional freight transportation system, and in particular several supply chains that operate in the system. .

4. A Multi-Modal State Freight Transportation Network

A multi-modal state freight transportation network should represent the rail, road, air, and marine infrastructure. This is necessary as a framework for storing and representing the flow of goods, and for considering the impact of changes to the infrastructure. We have selected a Geographic Information System framework, for which shape files have been obtained for all modes. We have taken advantage of publicly available data sources including the GeoMiler tool developed by the Bureau of Transportation Statistics. GeoMiler includes the infrastructure for all modes, cost for transportation on all links and through nodes, as well as capacities for all links and modes.

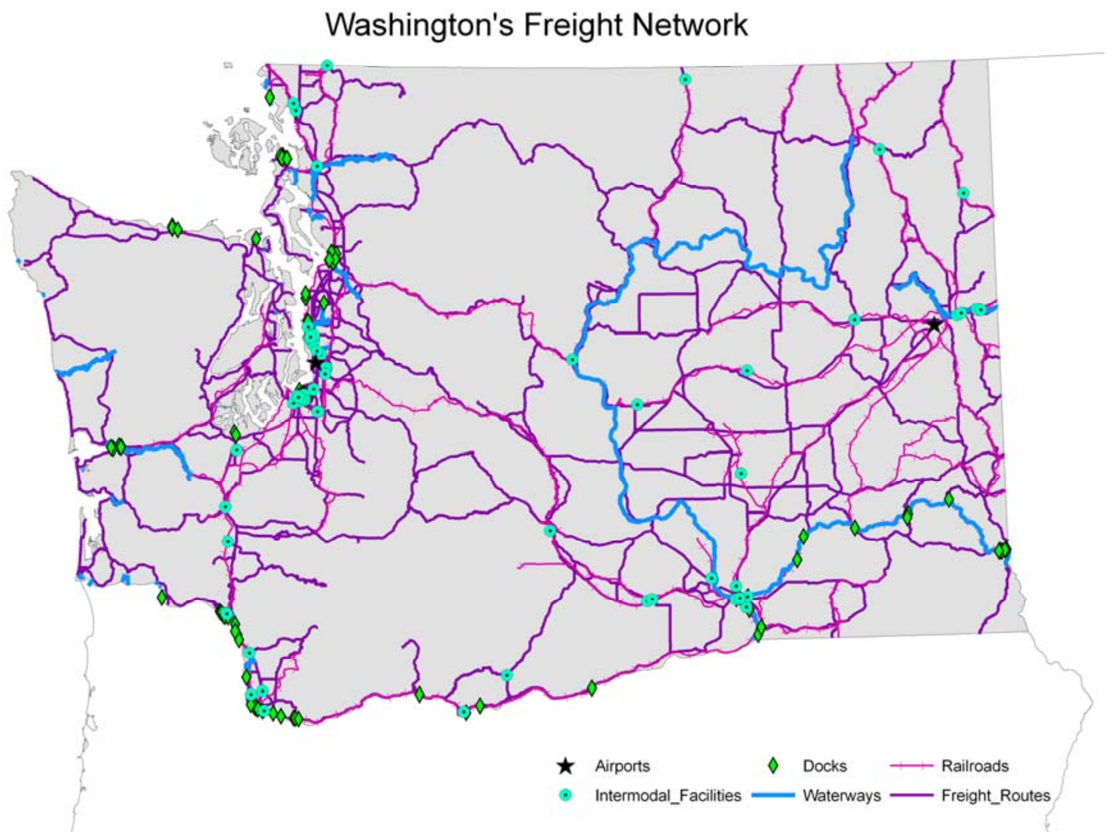


Figure 2 Multi-modal state freight transportation network

While it is reasonably straight-forward to represent the freight transportation infrastructure in Washington State, the goods flows are very complex. To estimate the economic consequences of disruption it is necessary to understand the nature of goods moving on a transportation link at a fairly detailed level. For example, we must be able to estimate the consequences of a two-hour delay, and therefore must understand the level of scheduling in the industry. Even given the limited availability of state-level goods movement data, we have decided on a methodology that takes a bottom-up rather than a top-down approach. Therefore, we have chosen to pursue a simulation type approach rather than use macro economic model such as an input/output models.

Consider the flow of goods in Washington State. We begin by, in Figure 3 splitting freight flows into international, national, and within state flows (Alaska is separated due to its reliance on Washington State facilities). The size of the various elements are not based on estimated volume of these flows.

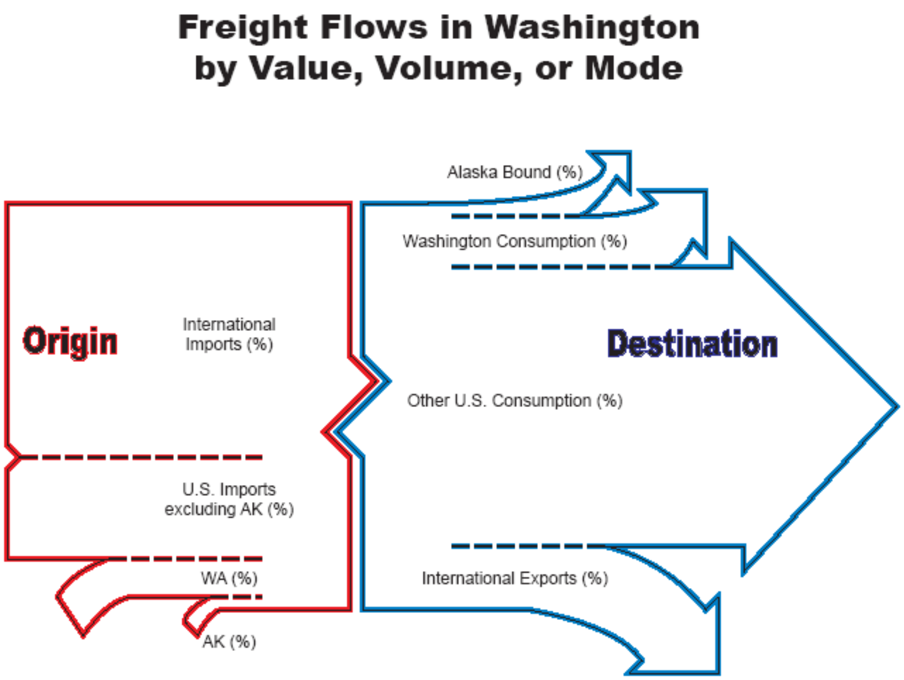


Figure 3 Washington State Freight Flows

Figure 4 shows the use of intermodal facilities by goods moving through Washington State, and Figure 5 shows the flow of goods within Washington State.

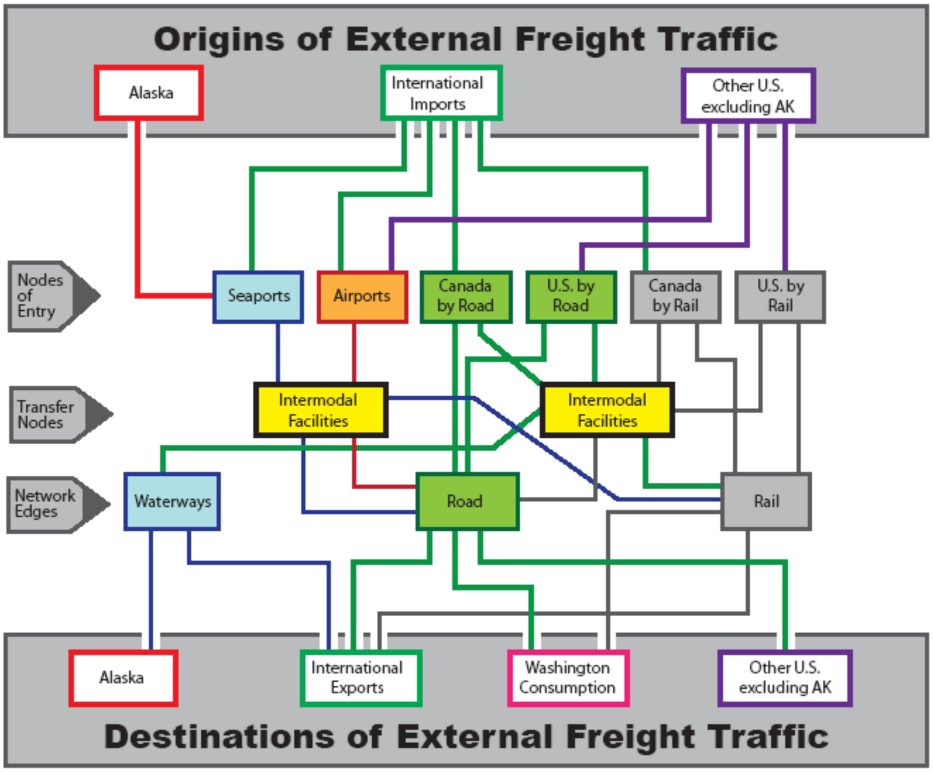


Figure 4 Flows of Freight through Intermodal Facilities through Washington State

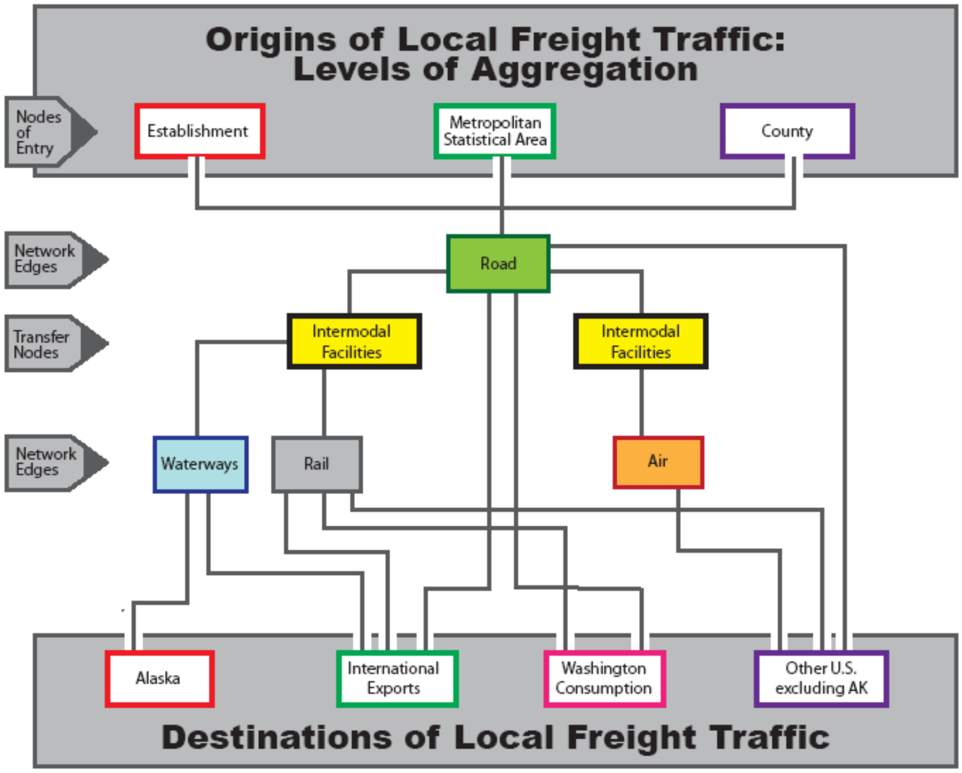


Figure 5 Flows of Freight through Intermodal Facilities within Washington State

Breaking this down further, Figure 6 shows Washington state freight movements simply at the intra and inter-state level.

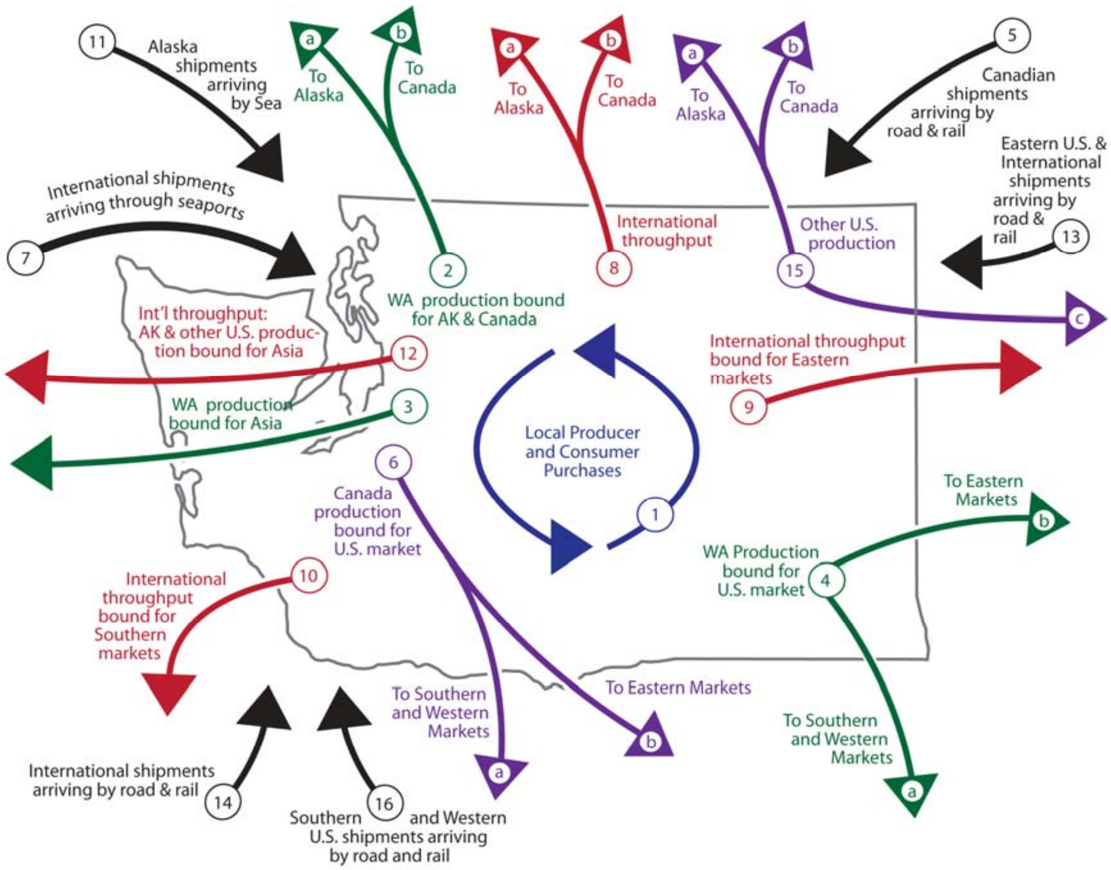


Figure 6 Intra and inter-state freight flows

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 7 Dependence of freight flows on intermodal facilities

Figure 7 shows the dependence of these flows on intermodal infrastructure. Even at this aggregate level the complexity of these flows can be conveyed.

5. Case Studies

With a simulation or operational approach, to fully capture the cost of transportation disruptions to the state economy, operational level detail would be required for industries moving goods within the state. This data is not currently available. We were aware of this limitation prior to the start of the project, and for this reason decided not to model all goods moving in the state, but rather to focus on a small number of case studies. We have decided to evaluate the impact of a one-day closure of I-90 at Snowqualmie Pass on the Washington potato industry. This potato industry case study is currently under development. We are still evaluating whether the state fuel supply system is amenable to a case study, but it is certainly an industry of interest.

5.1 Washington State Potatoes

A previous study completed by Washington State University for the Washington State Department of Transportation serves as a starting point for collecting detailed operational data on the potato industry Table 8 shows the export value of potato production in Washington State, which demonstrates the significant value of this industry.

Table 8 Export Value and Share of Potato Production in Washington State

	Year			
	2003	**2004**	**2005**	**2006**
Value of Washington Potato Exports ($ million)	196	234	264	309
Proportion of Total State Exports	0.6%	0.7%	0.7%	0.6%

Source: Total U.S. Exports (Origin of Movement) via Washington State, Foreign Trade Statistics

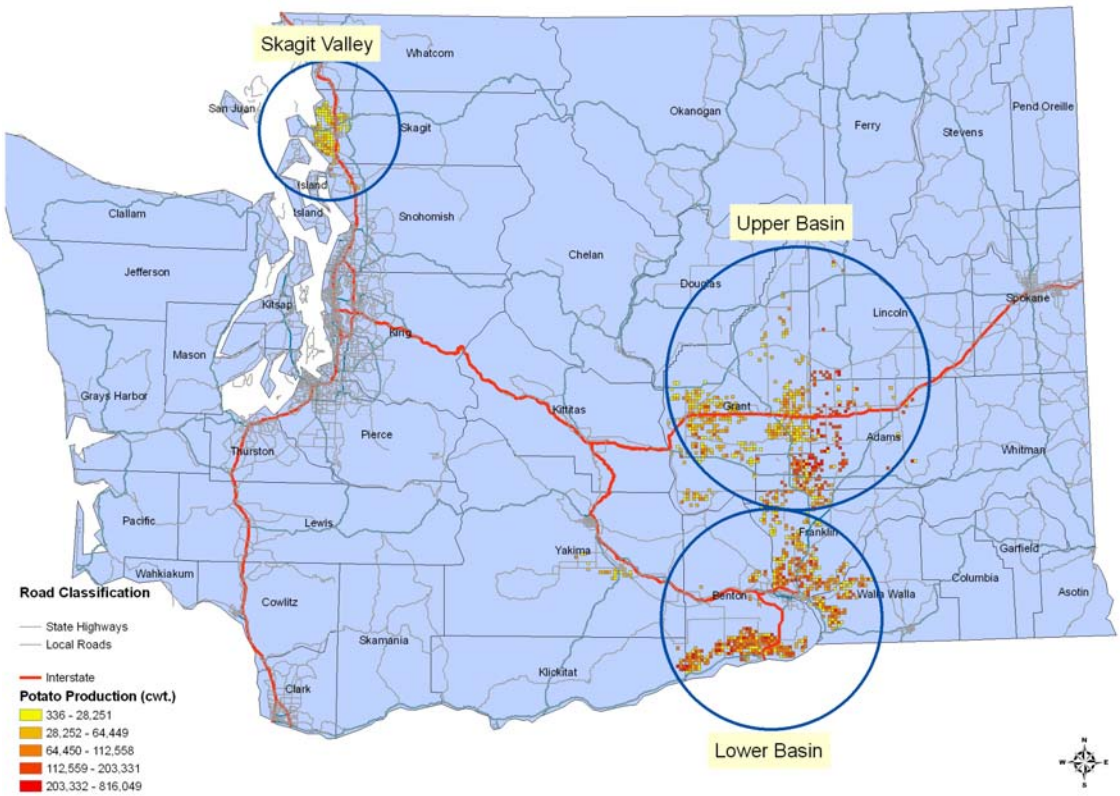


Figure 8 The location and intensity of potato production in Washington State.

Figure 8 shows the location and intensity of potato production in Washington state. As can be seem from this image the production is concentrated in three regions. This research project modeled these production regions as such, rather than identify each specific farm. Potatoes are moved from these locations to limited number of dehydrated potato processor locations, only one of which is in Washington. Potatoes are also moved to frozen potato processor locations, including three in Washington state. From these facilities potatoes are moved out of state, to grocery distribution centers, or to smaller retail opportunities such as individual grocery stores and farmer's markets. Modern distribution facilities serve very large regions, for example the Safeway distribution center for all of Western Washington north of Centralia is served from their distribution center in Auburn. The vast majority of the shipments from distribution centers are moved truck to final destination (TTF), and we assume all such flows within Washington state will move by truck.

The Washington State University potato study estimated the truck capacity for fresh potatoes to be 22 tons, and the truck capacity for processed potatoes to be 20 tons. These truck volume capacities were obtained from a weighted average of truck observations from the 2003 SFTA Origin-Destination Survey for trucks carrying fresh and processed potato products. The figures for processed production represent the volume of processed/packed potato products shipped out. Average recovery rate of Washington Potatoes during processing was assumed as 80 percent. Also, each potato production region is forecasted separately and converted into truck equivalents leaving each region. The information of how shipments leave and which highways are traversed to each destination were obtained from an industry survey.

Table 9 Proportion of Fresh and Processed Potato Production, by Region

Region	Fresh	Processed In	Processed Out
Lower Basin	45%	55%	44%
Skagit Valley	86%	14%	0%
Upper Basin	24%	76%	60%

According to these survey results, 86 percent of the total potato production in Skagit Valley is utilized fresh, while most of the Upper Basin potato is processed. However, since there are no processing facilities in the Skagit Valley, the outbound shipments from this area will be treated as entirely fresh, as the processing must occur in other locations. The “fresh” and “processed in” columns were obtained from the survey data, whereas the “processed out” column is the percentage leaving each region after applying the 80% recovery rate to that volume which is processed, with the only exception being the Skagit Valley (due to no processing facilities). Table 10 below presents the total volumes of production for each production region and the total number of truck loads required to transport fresh and processed potatoes to their final destinations.

Table 10 Potato Volumes (in Tons) and Total Truck Loads for Skagit Valley

	Volume (Tons)	Unique Truck Loads		
		Fresh	Processed	Total
Skagit Valley 2007 (estimate)	162,742	7,322	0	7,322
Lower Basin 2007 (estimate)	2,197,012	44,482	47,359	91,841
Upper Basin 2007 (estimate)	1,972,626	21,301	58,758	80,059

Among the three potato production regions in Washington State, the Lower Basin requires the most total number of truck loads to transport the fresh and processed potatoes to their final destinations. This is consistent with the region producing the largest volume of potatoes.

Table 11 Percentage of Shipments to Major Destinations by Region

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%

Source: 2007 Potato Survey

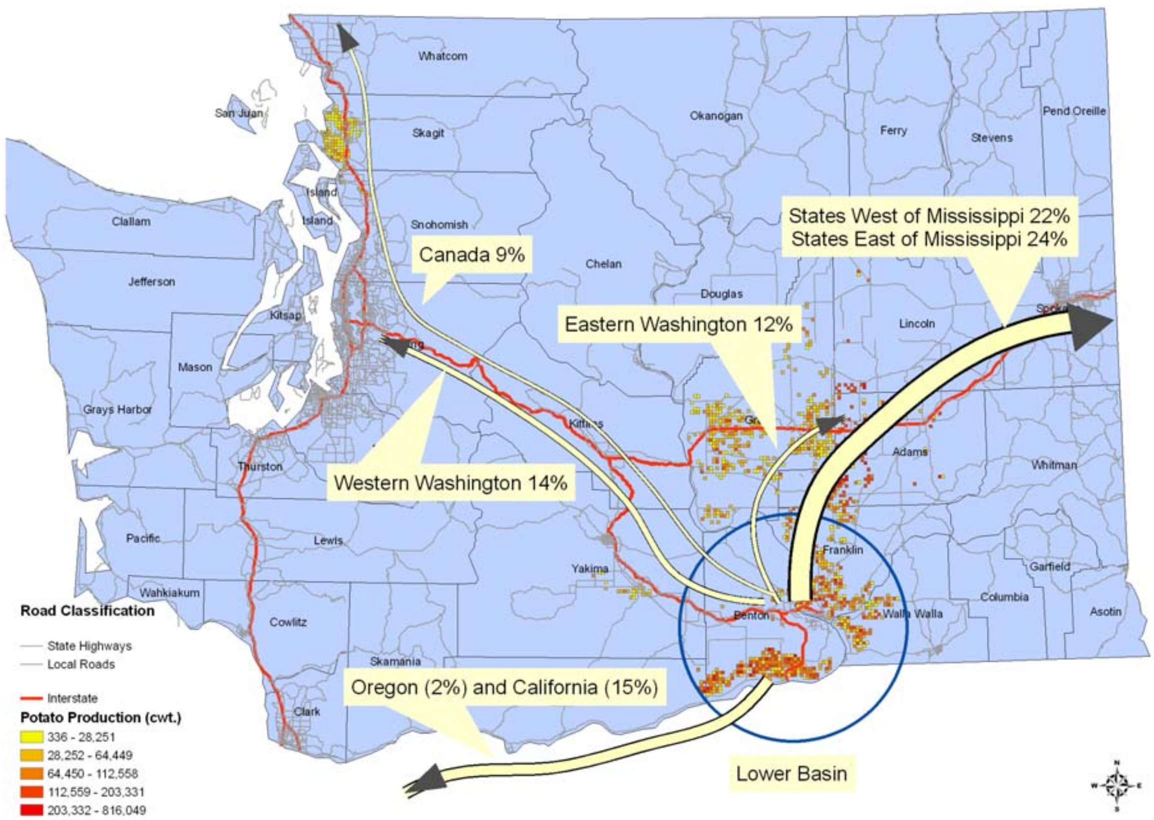


Figure 9 Shipment destinations for Lower Basin Potato Production

The shares of the production shipped from the Lower Basin, Skagit Valley and Upper Basin to their final destinations are provided in Table 11, and are geographically presented for each region in Figures 9, 10, and 11. Forty-one percent of the potato shipments in the Skagit Valley are sent to California. Forty-six percent of the shipments in the Lower Basin go to the States west and east of Mississippi, whereas thirty-four percent of shipments from the Upper Basin go to Idaho. Among the main production regions, Upper Basin is the sole provider of fresh potatoes and potato products to Idaho. Specific roadways used for flows on each of these origin destination pools will be identified by the GIS tool based on a least cost path assumption.

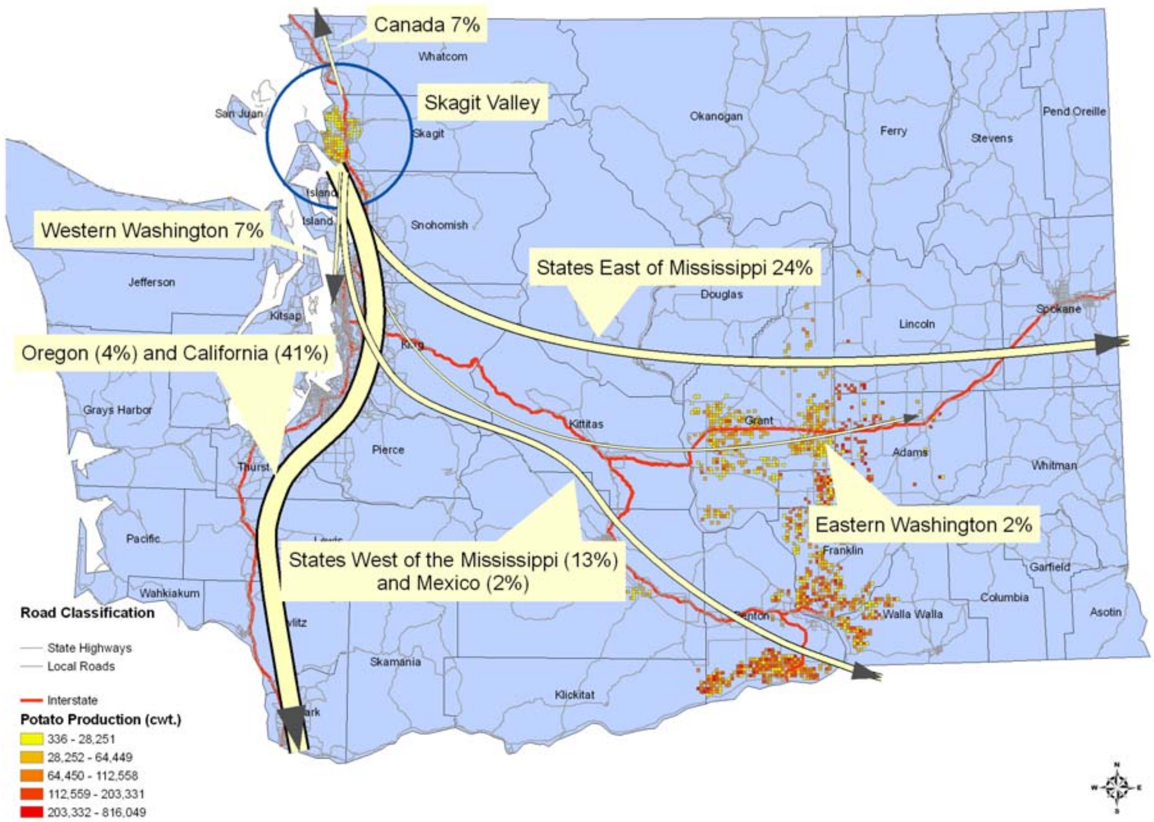


Figure 10 Shipment destinations for Skagit Valley Potato Production

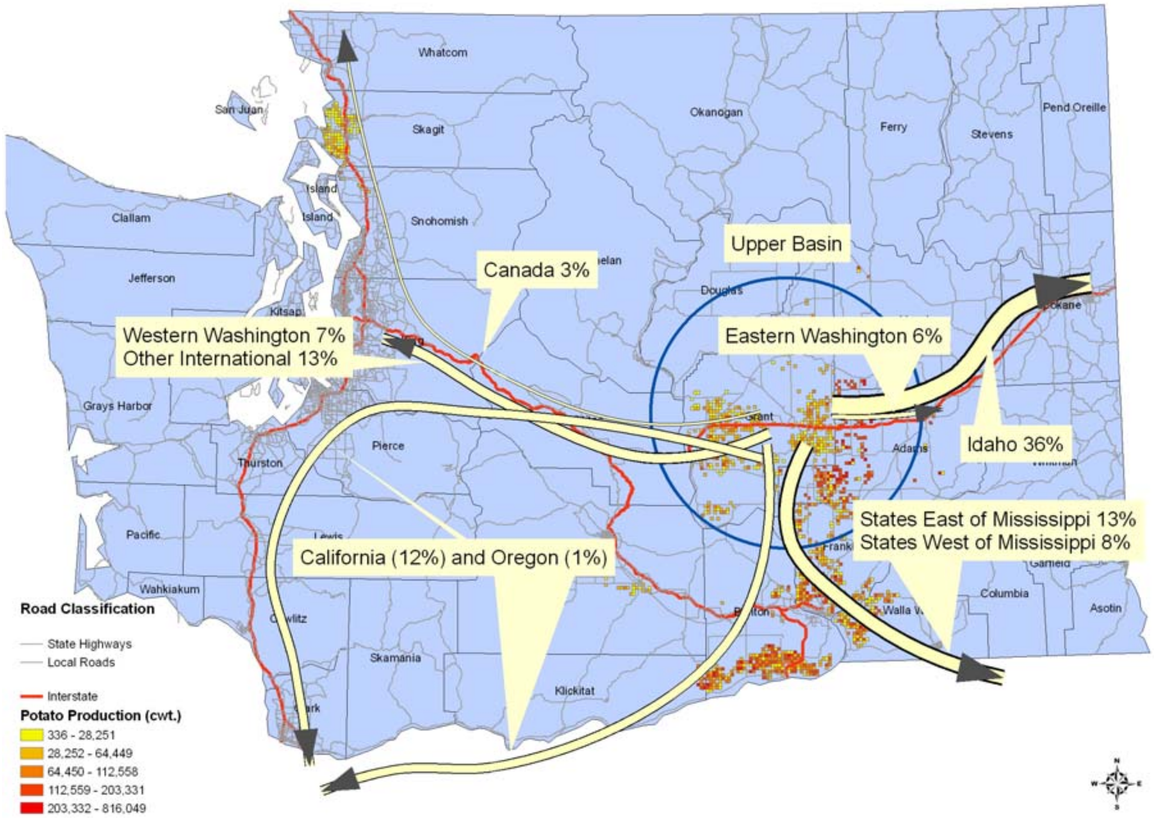


Figure 11 Shipment destinations for Upper Basin Potato Production

From the previous research, a geodatabase will be created that represents the movement of potatoes in Washington State. This will be linked to the shape files that represent the intermodal infrastructure, and a network will be created. The link representing I-90 will be removed, but the freight flows maintained. This will allow us to estimate the increased travel time required to move potatoes with the limited infrastructure. Given our knowledge of industry responses to disruption, the proportion of cancelled and delayed trips will be estimated and demand reduced proportionally. From this, the total cost of the disruption will be estimated.

5.2 Washington State Fuel Supply

Preliminary research to identify the quality and sources of information is underway.

6. Statewide Freight Model Stakeholder Meeting

In order to support customer use of the GIS freight tool, this research project will identify deliverables that met 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.

7. Conclusions

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

- 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
- understanding of current data and methodology used for freight planning in the state and the desires of the freight planning community moving forward

Ongoing work includes the completion of the two case studies. We have agreed on a bottom-up approach to meet WSDOT's needs with respect to estimating the impact of disruptions on particular industries, rather than use an aggregate approach.

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