ADDING RESILIENCE TO THE FREIGHT SYSTEM IN STATEWIDE AND METROPOLITAN TRANSPORTATION PLANS: DEVELOPING A CONCEPTUAL APPROACH

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FREIGHT TRANSPORTATION RESILIENCE: HOW A SYSTEM-WIDE PERSPECTIVE CAN HELP METROPOLITAN PLANNING ORGANIZATIONS AND DEPARTMENTS OF TRANSPORTATION

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SUMMARY

Advances in supply chain management have resulted in significant economic gains to corporations and consumers. These advances depend on a reliable transportation system to facilitate goods movement. The freight transportation system is an integrated network of infrastructure, carriers, and shippers that are engaged in the design, movement, manufacture, sales, and servicing of goods. This is largely a private enterprise, but much of the infrastructure that supports the system is publicly built and operated. Moreover, the infrastructure that supports these movements, especially in urban areas is operating at or above capacity and is aging. There is concern in the business community that the result of increased flows of freight and other traffic, when combined with the limited capacity and age of the system, are making the transportation system brittle in the sense that a small event could have far reaching adverse effects.

If the transportation system were instead resilient, it would be able to absorb small-scale events and recover quickly from large disasters. Resilience has been considered in the business and technical literature and has several key properties. These properties include: connectivity supporting multiple alternative paths among origins and destinations, and sufficient capacity and flexibility to use fully the alternative paths, possibly including alternative modes of travel. Resilience may be quantified by considering the change over time of the performance of the system as a result of a disruption. A disruption is an event that causes significant damage to transportation infrastructure, such as a terrorist attack or a natural disaster. Our formulation adds a temporal component: a resilient transportation system is one that minimizes both the initial effect of the disruption and the time required to return the system to normal operations.

Factors that enhance resilience of the transportation system improve responsiveness of operations (e.g., directing freight traffic to pre-identified alternate routes) and infrastructure repairs after a disaster to limit the effect of a disruption, and add capacity and provide flexibility (e.g., additional lanes, intermodal connection capacity, or bridges at river crossings) at critical intermodal connections or choke points in the transportation system in response to a disruption. Factors that degrade resilience are system congestion and obsolete infrastructure.

DOTs and MPOs may improve resilience by focusing investments and planning to address those factors that improve the resilience of the system. DOTs, in particular, can plan for disruptions, using experience from small disturbances and exercises to practice rerouting traffic and repairing quickly damaged infrastructure. The ability of DOTs to manage actively transportation system resources to meet demand and key needs is critical. Given their role in system planning, MPOs can improve resilience through building, maintaining, and applying transportation-planning models that capture the dynamic properties of the system. Incorporating additional system capacity into planning and direct engagement with the freight community to understand particular needs can also enhance resilience. Additionally, DOTs and MPOs must coordinate their efforts: If a DOT is to manage actively transportation system resources to improve resilience, resources need to be made available; and assuring that appropriate resources are available requires advance consideration of transportation system resilience by the MPO.

1. INTRODUCTION

Over the past 30 years, advances in supply chain management have resulted in significant economic gains. The widespread adoption of "just-in-time" management of inventory has resulted in significant economic gains, and relies on efficient and timely transportation and delivery of raw materials, works-in-progress, components, and final products. Disruptions to the transportation system require businesses to exercise contingency plans, traveling longer distances and holding more inventory, which increase costs and may erode the economic gains.

Over the same time period, the U.S. population and urban centers have grown significantly, while highway capacity has expanded little and much infrastructure has aged. The American Society of Civil Engineers considers U.S. infrastructure to be poorly maintained and obsolete; in particular it has concluded that a significant fraction of bridges are structurally deficient or functionally obsolete (ASCE, 2009). Similar concerns have been expressed about the rail freight system in the context of several decades of industry consolidation and system contraction amid increasing flows of freight (Weatherford, Willis, and Ortiz, 2008).

These developments are stressing U.S. transportation infrastructure. The growth in traffic volumes without commensurate increases in capacity "often means that even small disruptions can have a significant ripple effect on transportation system performance over a broad geographic region (FHWA, 2008, p. 1-6)." As a result, there is concern that the transportation system is brittle and that small and previously normal disruptions could cause the system to break (Ortiz et al., 2007). The implication for freight transportation is that economic gains made by firms optimizing their supply chains may be in jeopardy.

The opposite of a brittle system is a resilient one. Conceptually, a resilient system is able to provide services in the presence of small disturbances and recover quickly from large disruptions. Those designing and managing supply chains take into account the possibility of a supplier missing a shipment or a delay in delivery of key components and plan for such situations (Sheffi, 2007; Nishiguchi and Beaudet, 2000). In general, these approaches assume that the transportation system is able to accommodate the shifting demand. As ground transportation systems have become more congested and less able to accommodate shifting demand, improving the resilience of the transportation system itself becomes a priority.

In this paper, we analyze transportation system resilience from the perspective of metropolitan planning organizations (MPOs) and state departments of transportation (DOTs). MPOs are responsible for developing and maintaining short term and long term plans for managing and improving metropolitan transportation systems. DOTs perform a number of activities including emergency planning and response, infrastructure maintenance, and implementation of infrastructure expansion and improvement plans. We look at freight transportation as an example that raises important planning issues because freight transportation is largely a private enterprise that relies on and affects public infrastructure

Building and maintaining resilient systems is a common theme in the technical and business literature, which we connect to the roles and capabilities of MPOs and DOTs. We first describe the structure of the freight transportation system, identifying the actions that carriers and shippers take to make their own operations and supply chains resilient. Following with the discussion of the freight transportation sector, we discuss important aspects of resilience and explain how they relate to the transportation system. Building on these descriptions, we next discuss approaches for measuring resilience in freight transportation systems. To translate these approaches to freight transportation planning, we discuss the roles and responsibilities of MPOs and DOTs and how these measurement approaches may be relevant to efforts these organizations can undertake to improve transportation system resilience. Finally, we conclude by recommending future steps to translate these concepts into useful tools and guidance for MPOs and DOTs can take to improve resilience over time.

2. THE NEED FOR FLEXIBILITY IN THE FREIGHT TRANSPORTATION SYSTEM

The freight transportation system consists of integrated infrastructure, vehicle, contractual, and regulatory systems. The infrastructure components include sea and inland waterway ports, railroads, highways and roads, factories, distribution centers, and the interconnections among them. The vehicles are the cargo ships, barges, containers, airplanes, locomotives and railcars, trucks and tractor-trailers that move the goods through the system. Contracts among producers, suppliers, and consumers determine what goods are ordered and the price and pace of delivery. Finally, a group of domestic and international bodies oversee the activities of the freight transportation system to ensure compliance with health and safety regulations and trade agreements (Willis and Ortiz, 2004).

Public, private, and public-private entities own and operate the freight transportation system. With a few exceptions, the highway network is largely publicly built, operated, and maintained, with state DOTs typically being the lead agency. For example, Transportation Corridor Agencies operate private toll roads in Orange county California, and in 2007, Illinois leased the Chicago Skyway to Cintra Concesiones de Infraestructuras de Transporte S.A.. Port authorities oversee sea, air, and land ports and tend to be quasi-public agencies that have the power to issue bonds to fund infrastructure expansion and who work closely with private-sector tenants to ensure safe and efficient operation. Locks supporting inland waterway movements are publicly owned and operated. U.S. freight railroads are private-sector companies that own their right-of-way, track and locomotives, maintain and expand system infrastructure, and provide freight transport services to customers. Freight movements by road are performed principally by private sector trucking companies, who compete with each other by offering a range of services covering varying loads, distances, and rates.

The freight transportation system is an integral component of corporate supply chains, which have been a key enabler of economic growth over the past several decades. A supply chain is the "network of suppliers, manufacturing plants, retailers, and the myriad supporting companies involved in design, procurement, manufacturing, storing, shipping, selling, and servicing goods (Sheffi, 2007, p. 82)." Designing, managing, and operating supply chains is a business discipline that seeks to optimize the supply chain to meet a number of objectives, including: bringing products to market faster and reducing costs, which typically requires holding minimal reserve and work-in-progress inventory. A crucial component of these "just-in-time" practices is a reliable transportation system that delivers needed parts and materials very close to the time at which they are needed (Hillestad, Van Roo, and Yoho, 2009, p. 7).

There is a concern that congestion on U.S. highways, and limited capacity throughout the freight transportation system, will erode efficiency gains that occurred as a result of advanced supply chain management techniques (Ortiz et al., 2007). Moreover there is concern that the freight transportation system is brittle and that even small disruptions to the system could result in widespread effects throughout corporate supply chains. The rise in non-recurring congestion due to traffic incidents is one example of how disruptions affect operations (FHWA, 2008). Larger disruptions, such as the 2002 west-coast port lockout, or Hurricane Katrina, may have magnified effects throughout corporate supply chains.

The complexity of corporate supply chains requires that firms actively manage risks throughout them. Toyota, for example, maintains very close relationships with its suppliers so that failures throughout its supply chain can be accommodated. When a fire shut down a manufacturer of brake parts, Toyota was able to reconstitute the capacity quickly at alternative suppliers (Nishiguchi and Beaudet, 2000).

Accommodating disruptions within the freight transportation system often requires a variety of measures. This is because reliable freight transportation is a prerequisite for an efficient supply chain. Firms may hold additional inventory to accommodate the effect of unreliability in the transportation system. At a 2006 conference of shippers and carriers, an auto manufacturer described contingency plans to move critical, but heavy, parts via airfreight rather than containerized freight in case of a slowdown in the containerized shipping system (Ortiz et al. 2007). Depending on location, distance to be traveled, and the type of service being offered, there are sometimes opportunities to shift freight from truck to rail, and vice versa (Weatherford, Willis, and Ortiz, 2008). The availability of these options depends on appropriate linkages among the systems and the additional transactions and operations costs associated with ensuring increased supply chain flexibility. Ensuring flexibility to reduce corporate vulnerabilities and provide a competitive advantage has been the topic of detailed study (Sheffi, 2007).

This differs in significant ways from options available to facilitate passenger movement in the event of a disruption. In general, firms that move goods have a number of variables that they may control, including level of inventory, multiple suppliers and distribution centers, and mode. Management of the supply chain throughout a disruption is coordinated centrally. When confronted with a road closure or a system disruption, passengers may choose to take an alternative route or mode, wait until the disruption subsides, or forego the trip, but there is more rarely a central system of management to help them.

Since the freight transportation system, an inherently public-private entity, is such a key component of business operations, disruptions to it have the potential for widespread economic effects. The 10-day west-coast port lockout of 2002 has been estimated to have cost the U.S. economy $4.7 billion to 19.4 billion (in 2002 dollars), mostly as a result of delays that resulted throughout the system (Iritany and Dickerson, 2002; Cohen, 2002). In addition to supply chain effects, congestion on U.S. highways has many direct and indirect costs, including additional fuel burned, reduction in local air quality, and increased costs for goods and services that result; the U.S. Department of Transportation attempts to capture these effects for each U.S. metropolitan area (BTS, 2009).

A resilient freight transportation system is able to provide reliable services when it encounters small disruptions, and returns to service quickly after large disruptions. This study investigates what can be done to enhance resilient freight transportation service from the perspective of the MPOs who are responsible for planning transportation systems, and the DOTs responsible for construction, maintenance, and operation of transportation systems. Moreover, this study identifies measures that can help these public agencies work effectively with port authorities and the private sector to ensure that supply chains that rely on the freight transportation system are also resilient. Key to these tasks is formally defining resilience in the context of the freight transportation system, and developing appropriate metrics to characterize it; this is the topic of the following section.

3. WHAT DETERMINES RESILIENCE?

Resilience is a property of a system functioning as a whole, not its component parts. Formal analyses of resilience often considers networked systems, and as discussed above, the freight transportation system is part of a complex set of networks that enable corporate supply chains. In general, networked systems are defined as collections of nodes connected by links. The freight transportation network has as its nodes street addresses and intersections, rail stations, yards and interchanges, seaports, and airports. The links are roads, highways, tracks, sea and air routes that connect them. As discussed above, the private sector uses this physical network as the backbone of their supply chains, which include a network of contractual arrangements among suppliers, manufacturers, retailers, and other market participants. The public sector forms yet another network that interacts with both the freight transportation network and the contractual network (Willis and Ortiz, 2004). For transportation systems, MPOs and DOTs are the principal public sector actors. The efforts they take to improve the response of freight transportation are capable of affecting the extent to which disruptions to the transportation system disrupt freight movements and corporate supply chains.

This section reviews the relevant literature on networked systems and describes several concepts that can help transportation planners understand and manage resilience of the transportation system in general and the freight transportation system in particular. The purpose is to understand how the structure of the network and other factors contribute to resilience.

3.1 Structure has a significant effect on the performance of the network

How the nodes and links of a network are connected is known as the *network structure*. A network is said to be *completely connected* when there is at least one path from every node to every other node. In general for transportation systems multiple paths exist among nodes. The *characteristic path length* is the average number of links connecting any two nodes (Watts, 1999). When applied to transportation systems, alternative paths are typically ranked according to the number of modal changes, the distance, or the estimated total travel time.

Often a single bridge, tunnel, or other link connects portions of the network. If such a critical link is disabled, then the network becomes disconnected. Therefore, maintaining the connectedness of the network when nodes or links are disabled is key goal for system operators. Connectedness becomes an operational concern in two ways: (1) if certain key links (such as bridges and tunnels) are the only connections between parts of the network, and (2) if alternative paths between origins and destinations are mismatched in capacity, so that when a major link becomes unavailable, the alternative paths do not have the capacity to absorb the additional traffic. In general, transportation networks are densely connected in the sense that there are many alternative paths between any origin and destination. However, the relative capacity of the alternative paths may vary significantly.

3.2 There are two major types of resilience

Gunderson and Pritchard (2002) compiled a number of case studies investigating resilience in large-scale ecosystems under the influence of human behavior. Though focused on natural systems, their approach and results have relevance for infrastructure systems. These studies characterize two general types of system resilience, termed *engineering resilience* and *ecological resilience* (Gunderson and Pritchard, 2002).

Engineering resilience is measured by the time required to return to prior steady state operations after a disruption. Implicit in engineering resilience is the notion that the system is stable and has a single equilibrium condition representing the long-term steady state behavior of the system. Ecological resilience is measured by the magnitude of a disruption to the system that causes it to move to a different operating condition, stable or unstable.

Examples of disturbances to transportation systems can illustrate the concepts of engineering and ecological resilience. If a minor fender-bender occurs during rush hour on a limited access urban highway, it may require a few cars to move to the side of the road for a short amount of time. The small disturbance will result in slowed traffic in the vicinity of the crash, and it will return to normal flow thereafter. The system would be considered to have a high level of engineering resilience if the traffic flow returns to normal quickly after the disturbance.

Alternatively, suppose that a truck catches fire and disables a section of the highway for several weeks. An example of such an event is the truck crash, resulting pile up, and intense fire in a truck-only underpass of the I-5 freeway on October 12, 2007. The fire damaged the tunnel, requiring the I-5 freeway to be closed for several days and the tunnel to be closed for slightly more than a month ("Highway truck tunnel reopens after crash", 2007). That incident occurred on a Friday, and the freeway was reopened on Monday, sparing significant disruptions during the workweek. The tunnel remained closed for a month, however, and truckers expecting to use that tunnel had to seek alternative routes during the cleanup and repair phase, and others likely permanently changed their routes.

If the flows through the system did not change considerably as a result of the fire, and the effect of the closure of the tunnel were confined to vicinity, then that section of the I-5 and connecting roads is said to have a high degree of ecological resilience. This is because the relatively large disruption to the system, namely severing a highway freight link, did not cause the system to depart significantly from normal operations. This example also illustrates the interconnectedness of the freight and passenger transportation systems.

Given the needs of the supply chains that rely on freight transportation, it is important that transportation planners consider both the engineering and ecological resilience of the transportation system. In order to do this, it is helpful to know which system properties contribute to both engineering and ecological resilience.

3.3 Systems can build resilience by managing two network properties

According to the research of Gunderson and Pritchard (2002), the properties of large-scale systems that lead to resilience are *vulnerability* and *adaptive capacity*.

Vulnerability is the ease with which a disturbance may cause a system to deviate from its normal behavior; it is the sensitivity of a system to a disruption. In a system that is not vulnerable, the effect of a crash that disables a highway underpass on the flow of traffic throughout the system would be closely contained to the site of the accident.

Adaptive capacity is the ability of a system to devote resources to respond to a disturbance, thereby increasing the magnitude of a disruption that forces the system into an alternative state of operation. In the example of the I-5 tunnel fire above, the ability of adjacent highways and nearby surface streets to accommodate additional truck traffic.

Another concept similar to adaptive capacity that is used to characterize the performance of networked systems during disruptions is *flexibility*. According to Morlok and Chang (2004), a flexible system is able to accommodate changes in demand or traffic flows without significant declines in performance. To measure flexibility, they define "system capacity flexibility" as the "ability of a transport system to accommodate variations or changes in traffic demand while maintaining a satisfactory level of performance (p. 406)." Morlok and Chang (2004) cite two principal motivations for their approach to the analysis: (1) traffic is increasing while transportation infrastructure and capacity are roughly constant; (2) shifting trade patterns and sourcing strategies, namely a larger number of smaller shipments, are resulting in different demands on the transport system than were originally intended. They derive two measures of flexibility, the first is the maximum capacity (expressed in throughput) of a system based on a fixed traffic pattern, the second is the adjusted maximum capacity that allows for changes in the traffic pattern. In principle, Morlok and Chang's approach can be extended to the case where infrastructure is damaged, but that is not explicitly part of the analysis.

Feitelson and Salomon (2000) take a qualitative multidimensional approach to characterizing flexibility in the road, rail, and aviation transport networks, and the telecommunications network. To characterize flexibility, they describe these networks in terms of:

- the size and characteristics of a network node; e.g., the footprint of a rail switching yard, and the implications for management of flows through it and opportunities for expansion.
- characteristics of the links; e.g., the rail routes connecting yards and other loading and delivery points.
- flexibility over time to alter the operations of the network; e.g., by switching routes and modes.

In their analysis, Feitelson and Salomon rate each type of transportation system on each of these dimensions. Based on these assessments, they conclude that the road network is relatively flexible in structure and operation: Roads can be closed, directions can be changed, access can be limited when appropriate, and users are free to choose routes that serve their needs. In comparison, they conclude that rail systems are far less flexible: Once established, they are indivisible and require tight centralized control for efficient operation.

Feitelson and Salomon (2000) also analyze the effects of congestion on network flexibility. They examine network dynamics over the long term, as planners and users respond to congestion on existing networks by expanding capacity or altering behavior. This is similar to the activities of MPOs as they compile proposed changes to the transportation system, coordinating them into plans. Like Morlok and Chang (2004), Feitelson and Salomon (2000) see a future in which the traffic that the transportation network must accommodate is growing, but also one in which increasing capacity is becoming more difficult and the effects expensive. These trends are borne out by numerous analyses (see for example Sorensen et al., 2008). When confronted with similar challenges in the past, planners responded by building hierarchical infrastructures, such as the limited access highway system, that have higher capacity, but fundamentally are less flexible than the freely accessible networks they augment. In general, metropolitan areas in the United States have road transportation networks that consist of both limited access highways and surface streets.

Within corporate supply chains, capacity and flexibility are the two key attributes that firms use to manage resilience (Sheffi, 2007). As mentioned earlier, the simplest way to maintain a resilient system is to maintain additional inventory, idle capacity, or other redundancies that can be called upon in the event of a disruption. Alternatively, designing and implementing a flexible supply chain might include being able to interchange key parts, or alter the scheduling of key manufacturing steps to be able to better match supply and demand. Both of these strategies have value when assessing the resilience of corporate supply chains to disruptions in the transportation system.

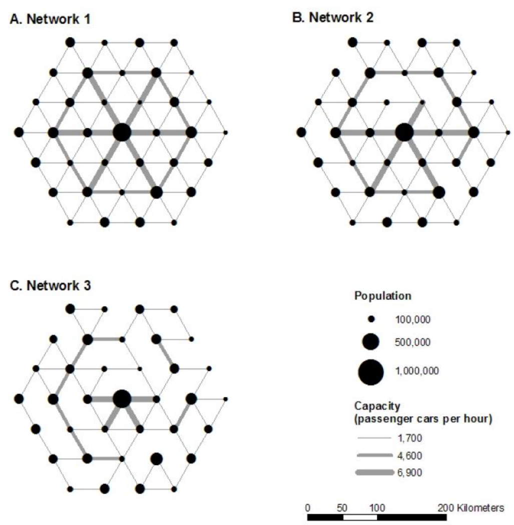
The approaches of Feitelson and Salomon (2000), Morlok and Chang (2004), Sheffi (2007), and others, are important, but they do not analyze how transportation system planners and operators build and maintain a system to improve its resilience. Stated in the context of the purpose of this report, what are the key steps that MPOs and DOTs can take to improve resilience of freight transportation? To begin to address this question, we first turn to a related body of literature that explores the topic of *robustness* in transport systems; later we will consider specific actions MPOs and DOTs may take in light of their results.

The focus of studies of network robustness is the development of performance measures that characterize overall system performance and how each individual link contributes to it. Scott et al. (2006) develop and apply a "network robustness index", incorporating a measure of network performance, to facilitate highway system planning. Scott et al. (2006) calculate the network robustness index as the additional total travel time for all users required to meet demand when a single link in the system is removed at random. The goal is to identify the links that (1) play an essential role in maintaining network flows and whose removal results in large performance penalties, and (2) enhance network robustness by absorbing traffic flows when a link is removed or disabled.

Scott et al. (2006) demonstrate that using such a network-wide performance measure can result in different choices regarding system expansion than a link-by-link analysis based, for example, on the isolated performance criterion such as the ratio of the volume of traffic to the capacity of the roadway. They describe three networks, each with the same number of nodes and traffic patterns, but with different connectivity among them in terms of both links and capacity. The networks considered by Scott et al. (2006) in their analysis appear in Exhibit 1 below. In the most connected network (Network 1), the connectivity results in the availability of additional paths through the network, minimizing the effects of a disruption. In this case, volume-to-capacity ratio is a good indicator of the contribution of a link to the performance of the overall system. As the connectivity among nodes decreases, essential links exist without which the network has significant difficulty meeting demand. Through a sequential ordering of links, Scott et al. (2006) show that the links identified as most important by the network robustness criterion are often different from those identified by an ordering of their volume-to-capacity ratios. This phenomenon is most pronounced for Network 3, the least connected network.

To date, such analyses have used relatively simple computer models of transportation networks to demonstrate the viability of their approaches. Applying such an approach to planning and operations would require the development of new planning models, the collection and analysis of data regarding how actual systems operate when disabled, and the formulation of additional measures of performance. We will revisit this topic during the discussion of transportation planning models commonly used by MPOs later in the text.

Exhibit 1. Three Road Networks with Different Connectivity among Nodes.



Source: Scott et al. (2006)

4. MEASURING RESILIENCE OF TRANSPORTATION SYSTEMS

The concepts of robustness, engineering resilience, and ecological resilience that were introduced in the previous section provide a starting point for discussion of how to measure resilience (Gunderson and Pritchard 2002). However, to measure resilience in a way that is meaningful for transportation systems it is important to understand where performance of the system may degrade, and when it does, how performance changes over time. To capture these aspects, we propose building on the work of studies of how natural disasters affect critical infrastructures (Dalziell and McManus, 2004; Tierney and Bruneau, 2007; and Shinozuka et al., n.d.) to develop a time history of a disruption to a transportation network and the performance of the system as it responds to that disruption. We then connect the insights we gain from the technical analysis to the planning and operational needs of MPOs and DOTs.

Disruptions are events that cause enough damage to degrade significantly the performance of the system. Such events push the transportation system to a new operating state, potentially overwhelming the ability of the system to adapt to the disruption. This is in contrast to a *disturbance*, which is an event that produces temporary effects, such as a minor accident. There are four types of disruptions, summarized in Exhibit 2 below.[1]

Exhibit 2. Canonical Disruptions to Transportation Infrastructure

Disruption	Example	Description of effect
Terrorist attack	2004 attacks on Madrid commuter rail	Localized damage and disabling of transportation system
Infrastructure failure	Collapse of I-35 bridge over the Mississippi river in Minneapolis/St. Paul	Single point failure
Major accident	Crash, pileup, and fire in I-5 underpass.	Localized damage and disabling of system
Natural disaster	Hurricane Katrina; Northridge earthquake	Significant widespread damage

Terrorist attacks may target persons or elements of infrastructure. For example, the attacks on the Madrid commuter rail system consisted of coordinated bombings killing nearly 200 persons. In addition to the loss of life, there was minor damage to rail infrastructure. The collapse of the World Trade Center destroyed several subway and underground rail stations and disabled the local road network.

Second, infrastructure may fail. The collapse of the Interstate 35 bridge in Minneapolis was a sudden event that severed a key transportation link.

Third, major accidents may also cause significant disruptions. One example is the truck crash, resulting pileup and fire that temporarily shut down the I-5 freeway north of Los Angeles in 2007.

Finally, natural disasters cause widespread damage to the transportation system, requiring a comprehensive approach to assessing damages and reconstituting the transportation system.

[1] By listing the classes of disruptions that might disable a transportation system, we do not mean to imply that the response needs to be tailored specifically to each specific cause. Rather, standard practice in emergency response is to take an "all hazards" approach to emergency response planning and execution, which focuses on mitigating the effects of a disruption. A similar approach is advocated for supply chains (Sheffi, 2007) and for freight transportation (MIT, 2008).

In Exhibit 3, we illustrate how resilience is determined by how a system responds over time to a disruption. The horizontal axis of Exhibit 3 is time and the vertical axis is the measure of the disruption's effect on the transportation system. This measure may represent a number of alternative aspects of system performance, including: travel time (Cascetta, 2001); the flow of freight units over time; percent of the population receiving essential services (Shinozuka et al. (n.d.); general cost (Nagurney and Qiang, 2007); or in the aggregate through a metric that is constructed to reflect the combined effect of each of these factors such as the network robustness index (Scott et al., 2007) or a general measure of infrastructure quality (Tierney and Bruneau, 2007). A *performance baseline* may be established for a transportation system; this is indicated by the origin of the vertical axis in Exhibit 3.[2] As was discussed above, the performance of a transportation system varies over time as a result of hourly, weekly, or seasonal demand changes. For example, the normal travel time into a central business district will likely vary depending on the hour of the day, the day of the week, and the season. Minor accidents and scheduled maintenance also have an effect on the throughput of a transportation system, but in general should not be considered to be significant disruptions. These minor disturbances are consistent with the notion of engineering resilience from Gunderson and Pritchard (2002) in which the system performance remains close to a stable equilibrium. This natural variation in system performance is indicated on Exhibit 3 by a horizontal dashed line. Any variation in system performance below this level of natural variation, for example caused by daily congestion or regular maintenance, can be considered equivalent to normal system performance.

Suppose now that a disruption from those listed in Exhibit 2 pushes the transportation system away from this performance baseline. There are two phases to the event, which we describe below:

Phase I - Disruption. In the figure, we mark the time the disrupting event occurs as t_0 and the time when the effects reach their peak as t_1. The duration of Phase I is the elapsed time between these two times. During this phase, a catastrophic event occurs that causes a disruption to the system, disabling key nodes and links. For example, the Loma Prieta earthquake of 1989 caused a 50-foot section of the San Francisco Bay Bridge to collapse, indirectly killing 1 person and cutting off an essential link in the regional transportation system. Once the physical damage to the bridge was done, the effects of the disruption on traffic flows and system performance propagated through the network, increasing until they reached a peak. During this period, the California DOT, emergency responders, and the Metropolitan Transportation Commission (MTC) engaged in emergency response activities and initial assessments of the damages and their implications. At the same time, users of the transportation system began to alter their behavior.

Phase II - Recovery. In the figure, this phase begins at t_1 and ends at t_2. During this phase, damaged system components are repaired and put back into service. If there is sufficient adaptive capacity in the system which provides adequate alternative routes and the capacity to manage traffic flows[3], then the time to return to near baseline performance may be quite short. Also, if the event does not significantly damage key infrastructure, recovery time may be quite short, on the order of days or weeks, with a correspondingly quick return to normal operations. If, however, the event destroys key infrastructure, and insufficient system resources exist to accommodate the shifts in demand, then the time to recover completely may be quite long, perhaps months or years.

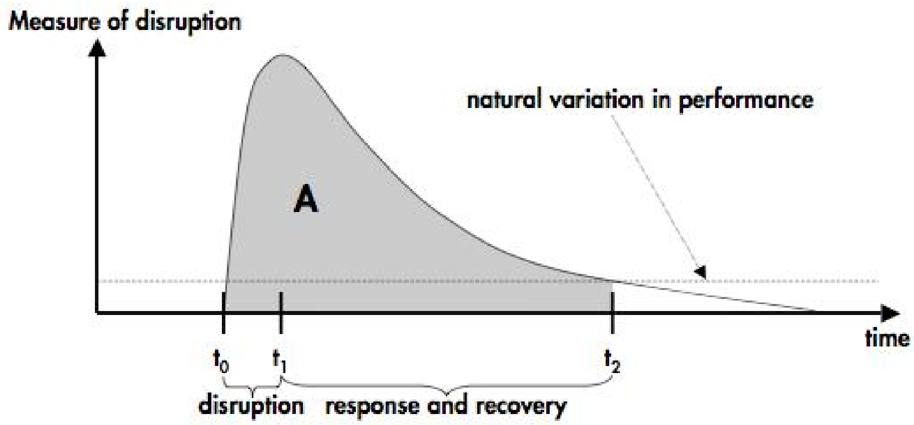
If the measure represents a flow, such as containers per unit of time, for example, then the area underneath the disruption curve in Exhibit 3 - indicated by A in the figure - represents a physical quantity - e.g. containers whose travel is affected during the disruption. In many cases, this measure can be thought of as the cost. This observation leads us

[2] This is very similar to the approach taken by Dalziell and McManus (2004) to characterize the resilience of organizations.

[3] The adaptive capacity discussed here could be achieved through two mechanisms. One would be constructing sufficient redundant paths in the transportation network, such as additional bridges crossing rivers. A second approach would be to enhance the responsiveness of transportation system operations to the needs of the freight shippers through improved communications and information sharing with the private sector so that certain freight flows may be prioritized, minimizing the regional economic impact of the disruption.

therefore to an objective for managing resilience: a resilient transportation system will minimize the area A in Exhibit 3, by limiting the magnitude of the effects of disruption, shortening the period of recovery, or both.[4]

Exhibit 3: Time History of a Disruption to a Transportation System



Note: Y-axis represents the negative change from nominal performance.

The measure of disruption depicted in Exhibit 3 should represent an aggregate measure of the performance of the system. In practice, several measures of performance may be adopted, representing different aspects of system performance. These might include *throughput* as the measure of actual performance and *capacity* as the measure of theoretically achievable performance. Travel time and distance between points of interest in a network may be important for certain goods and trips. Local air quality and noise may also be measures of interest. Selecting the appropriate measures of performance is critical because those measures guide public and private investments in the system. We discuss options for these later in the context of DOT response and construction activities, and the MPO planning process.

4.1 Applying network resilience concepts to the freight transportation system and to effects on corporate supply chains

The above framework presents resilience as a consequence of how the transportation system reacts to a major disruption. Here we apply this general concept to the more specific performance of the freight transportation system, and indicate possible effects on the corporate supply chains that are dependent on it. We do this in three parts: first, we explore alternative measures of the disruption that may be more relevant to the largely privately owned and operated freight transportation system; second, we illustrate how disruptions may affect freight transportation differently than they do the larger transportation system.

Carriers and shippers in a region assess the performance of freight transportation and the effect on supply chains using measures of performance that take into account the type, value and time-sensitivity of the goods being moved, the costs of movement, and the effects on business operations. A disruption to the freight transportation system alters the flows of goods, disrupting business operations, and incurring a cost. This is different than a general measure of performance for a larger transportation system in which each trip through the network is treated equally. The data required to assess the performance of freight transportation likely will not be available publicly, so DOTs and MPOs may have to partner with

[4] Tierney and Bruneau (2007) term the time history of the disruption and repair to the infrastructure the "resilience triangle." The formulation of Shinozuka et al. (n.d.) also has a triangular shape over time.

carriers and shippers in their region to understand how the disruption affects their operations and what public sector actions might be appropriate to facilitate recovery.

When a disruption to the freight transportation system occurs, the effects vary by carrier and shipper depending on the location and extent of the disruption, and whether it disproportionately affects freight transportation. A natural disaster, such as the Northridge earthquake that damaged large sections of the I-10 freeway in Los Angeles, may incur widespread damage to the transportation system, and affect all users. Other disruptions affect freight more than they do other traffic flows. For example, after the crash and fire in a tunnel under the I-5 freeway in Santa Clarita, California, the freeway was reopened within several days, but the tunnel remained closed for over a month. As a truck tunnel, its purpose was to facilitate freight movements through the area. Other disruptions may affect freight-specific infrastructure, such as ports or distribution centers.

The time history of a disruption to freight transportation has a similar trajectory as illustrated in Exhibit 3, but actions taken to improve resilience may differ from those of the public sector. As discussed earlier, businesses employ a number of strategies to improve resilience. UPS maintains an ability to shift modes from rail to truck, and vice versa. It also flies empty aircraft to offer relieve in the case of a mechanical problem. Manufacturers and retailers may maintain additional inventory or may have relationships with alternative suppliers so that they may be able to maintain business operations during a disruption to their supply chains. All of these actions seek to reduce the peak of the disruption and the time needed to recover, both of which improve resilience.

Disruptions to the transportation system often require the coordinated activities of the public and private sectors to ensure freight transportation flows, both for emergency response and economic recovery. Recently, the Washington State Department of Transportation (WADOT) and the Massachusetts Institute of Technology Center for Transportation and Logistics (MIT-CTL) completed a study regarding the development of a freight resiliency plan for Washington (MIT, 2008). This study focused on minimizing the economic effects of a regional disruption to the transportation system. Minimizing economic effects, in part, requires that the needs of private sector supply chains be considered as the public sector responds to a large-scale disruption. As part of their research, the WADOT and MIT-CTL team categorized the types of freight flows through the transportation system and their importance to the regional economy. Using this information, they were able formulate a response plan to minimize the economic effects: For example, one high priority action would be to restore outbound container traffic from the Ports of Seattle and Tacoma, which would allow businesses to continue export transactions. This example illustrates the essential coordination with the private sector that is needed to ensure that the components of the state plan address key supply chain needs. Close coordination with the private sector is also important to ensure the flow of needed supplies during emergency response activities. The WADOT and MIT-CTL results complement the framework presented here because they provide a means of prioritizing alternative DOT actions to assist in the response and recovery to a disruption, reducing the magnitude of the disruption, as illustrated in Exhibit 3, to both the public and the private sectors. Careful consideration of public and private benefits when considering alternative actions is essential.

4.2 Conditions that enhance or degrade transportation network resilience

In addition to the structure and capacity of a transportation network, the conditions under which it operates contribute to its resilience. These conditions have an effect on the ability of the system, operators, and users to respond to the disaster. Exhibit 4, below, summarizes some of these conditions and their effects. Recall that a resilient system is one that limits both the magnitude of a disruption and recovery time through the appropriate allocation of system resources. The actions of MPOs and DOTs may affect the conditions of a transportation network that determine its resilience. These conditions include whether or not the system is congested, whether alternative routes and modes exist for accommodating traffic, and whether appropriate plans for rerouting traffic around a disruption are in place and can be implemented quickly. Each of these conditions will have an effect on the magnitude of the disruption and the time to recover. Exhibit 4 indicates the likely marginal effect that the condition will have on the magnitude of the disruption or the recovery time: an up arrow indicates a positive effect on resilience, a down arrow indicates a negative effect, and a dash means the effect is neutral.

Exhibit 4: Conditions that Enhance or Degrade Transport System Resilience

Transportation network operating conditions	Description	Disruption		Response and Recovery	
		Direct effects	Indirect effects	Contingency operations	Infrastructure repairs
	Characteristics of a resilient system	Minimal lives lost and infrastructure damaged or destroyed	Minimal additional travel time and costs due to user rerouting or lost trips in reaction to the disruption	Ability to accommodate demand through alternative routes, mode shifting, etc.	The ability to quickly return to service damaged infrastructure at or near prior capacity
Congestion	Network links operating at or above rated capacity	-	↓	↓	-
Connectivity and flexibility	Multiple alternative paths exist for any given origin and destination, including alternative modes	-	↑	↑	-
Excess capacity	Links throughout system are operating below rated capacity	-	↑	↑	-
Aging infrastructure	Key infrastructure components are past designed lifetime and possibly deteriorating	↓	↓	-	↓
Emergency response	Capability of first responders and DOTs to execute a coordinated response	↑	↑	-	-

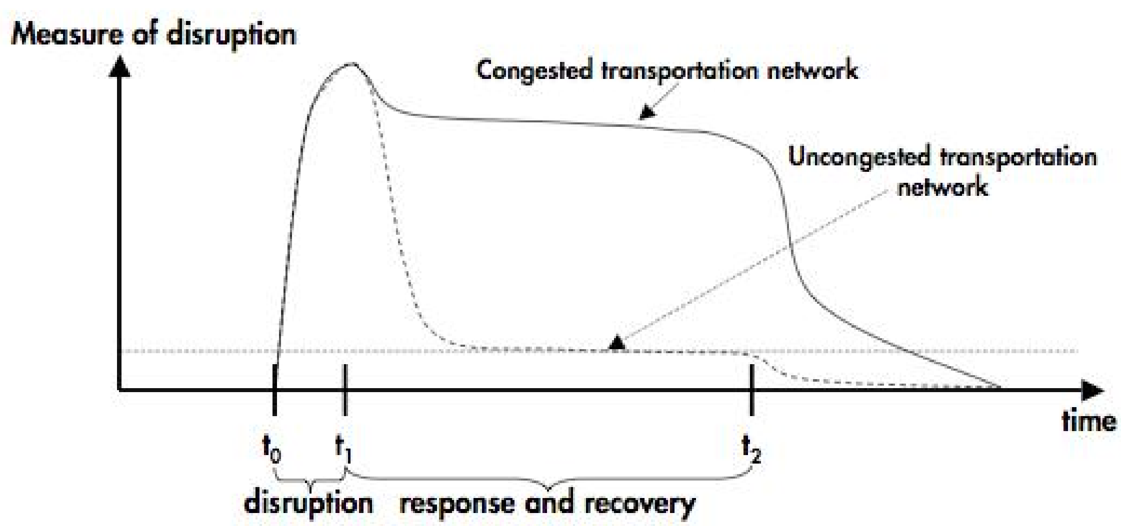
If the network is already operating at or above capacity, then a disturbance to a single network link propagates quickly through the system. In this case, the effect of larger-scale disruptions, as listed in Exhibit 2 is amplified. Conversely, if the system is highly connected and flexible and contains many alternative paths, there will be less disruption to users. If a system has excess capacity, it can more easily accommodate a disruption and is therefore more resilient. If the network infrastructure is aging, the potential effects of a disruption are greater: The disruption itself may cause severe damage, in turn requiring extensive and time-consuming repair or replacement. Within a region, the affect of aging roads and bridges is therefore an increased likelihood of large disruptions due to failure of the physical infrastructure. This degradation of resilience is experienced and perceived much differently than the constant drag of congestion, but can have an equally detrimental effect on the functioning of freight supply chains. Finally, capable emergency response, including advancing planning and quick implementation of transportation alternatives to accommodate emergency, freight, and passenger flows, will reduce the magnitude of a disruption.

Among these conditions, those that cause greater variations in transportation system performance are increased congestion and aging infrastructure. This is because, as discussed above, congestion and deteriorated system components tend to magnify the effect of disruptions, further degrading system performance over what would otherwise be the case. For example, as traffic in Los Angeles has increased over the past several decades without commensurate increases in system capacity, the amount of time the roads are congested each day has increased as well (Sorensen et al., 2008). Nationwide, non-recurring congestion as a result of accidents, weather, construction, or special events, now accounts for approximately one-half of travel delay on U.S. roadways (FHWA, 2008). This is a general decline in system performance when compared to the performance of the road network compared to its performance in the past.

As an example of how adaptive capacity, as discussed in the literature review, affects resilience of a transportation system, consider the time history of a disturbance for two systems. One system is congested and has little adaptive capacity, while the other is uncongested and has a significant amount of adaptive capacity. Because the first transportation system is operating at or near capacity prior to a disruption and at or over capacity after a disruption, the travel time and costs to users during the repair of the system are greater than they would be otherwise. When the repairs are complete, the transportation system can return to its normal operations, meaning that it will operate once again with traffic slightly below capacity, but still sensitive to disruptions. On the other hand, the system with a large amount of adaptive capacity causes minimal additional travel time and little or no costs to users when a disruption occurs. In Exhibit 5, the area beneath the curve for the congested transportation system is significantly greater than that for the uncongested transportation system.

These concepts apply when we consider only the freight transportation system and shippers whose supply chains depend on it. The degree to which carriers can reroute freight around the disruption or onto alternative modes has a significant effect on the resilience of freight transportation. Similarly, those carriers who have contingency plans that specifically address likely disruptions to freight transportation will fare better than those that do not. In many cases, close coordination with the public sector to prioritize those freight flows critical to the regional economy further assists in recovery (MIT, 2008).

Exhibit 5: Time History of a Transportation System Disruption for Congested and Uncongested Systems



5. ORGANIZATIONS AND ACTIONS TO MITIGATE AND RESPOND TO DISRUPTIONS TO TRANSPORTATION SYSTEMS

Emergency management agencies, DOTs, traffic management centers, and MPOs play overlapping roles in building and operating the transportation system, and mitigating the effects and responding to disruptions to it. Exhibit 6 lists the principal public-sector organizations and their roles in improving resilience. This section explores actions that these organizations can take, often in collaboration with the private sector, to improve the resilience of the transportation system and of freight transportation specifically.

Exhibit 6: Actions Organizations May Take to Improve Transportation System Resilience

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

State DOTs and emergency response agencies are those that are most directly involved in planning for and responding to disruptions to transportation systems. In general, state DOTs have dual roles: They coordinate transportation-related response activities, including both ensuring accessibility for emergency support services and for planning and reconstruction of network assets. MPOs are responsible for long-term transport system planning and can improve resilience through appropriate planning for redundancy and system flexibility. Recently, there has been a focus on more tightly integrating operations activities of DOTs and the planning activities of MPOs (FHWA, 2008). Further exploring these responsibilities provides insight into opportunities to improve the resilience of transportation systems, and the goods movements and supply chains that depend on them.

5.1 Emergency management agencies coordinate responses to transportation disruptions

Responding to disruptions, such as those presented in Exhibit 2, are likely to require emergency response activities in addition to activities to repair any damage to transportation infrastructure. Primary initial responsibility for emergency management is at the local level, but often state and federal resources are required to respond to an emergency. Federal assistance comes from the Federal Emergency Management Agency (FEMA), which is part of the Department of Homeland Security (DHS). At the state level, the lead agency for emergency preparedness and recovery is the state emergency management agency. Since September 11, 2001, all states also have an office of homeland security to serve as the primary liaison with DHS for security planning and response.

The Federal Emergency Management Agency requires states to maintain two plans for responding to incidents. The first is an emergency operations plan (EOP) that spells out the responsibilities, lines of communication, and actions to be taken in the event of an emergency. [5] In general, EOPs are organized by emergency support function (ESF), which includes transportation, communications, public works/engineering, firefighting, resource support, hazardous materials, and food. The second is a mitigation plan, which is designed to reduce the potential impacts of natural disasters and terrorist attacks. State plans are categorized as *standard* or *enhanced*, with enhanced plans meeting higher requirements for the approach to mitigation and effective administration of existing programs. States with approved enhanced plans are eligible to receive additional funding through FEMA's Hazard Mitigation Grant Program (FEMA, 2008a). Effective emergency operations plans may be able to reduce the impact of a disruption while it is occurring - reducing the height of the curve in Exhibit 3 - and effective mitigation plans may improve resilience by reducing the overall damage from a disruption and speeding the recovery process (see "Response and Recovery" in Exhibit 3 and Exhibit 4).

Planning and coordination often focuses on capabilities required to respond to effects resulting from likely disruptions. For example, the Washington State Enhanced Hazard Mitigation Plan meets the enhanced standard and includes specifications for state and local coordination, a hazard mitigation strategy, and risk assessment guidelines that address the nine natural hazards judged most likely to occur in the state (terrorism and other human-caused disasters are not included in this plan). It also includes plans to upgrade the state's critical bridges and investigate an early-warning system for landslides near key transportation routes (State of Washington, 2008). By planning specifically for the effects resulting from the most likely natural disasters, Washington ensures that the appropriate scale and skills of emergency-response resources are available, mitigating the effects of the disaster and improving resilience. Moreover, if Washington were to bolster vulnerable infrastructure such that it would be likely to survive a disaster, and continue to provide services throughout the period of response and recovery, both the magnitude of the disruption and the length of time required for response and recovery would be reduced. Within the measurement approach presented in Exhibit 3, these actions would improve further resilience.

5.2 State DOTs are transportation system operators

State DOTs are responsible for day-to-day maintenance and operations of the transportation system and for many functions in response to disruptions to the transportation system. Thus, DOTs play important roles in ensuring the transportation network resilience in their respective states. Among the roles assigned by state EOPs to DOTs are evacuating people, transporting emergency supplies, determining alternative routes if major modes or corridors are

[5] Authority for this requirement is provided by the Robert T. Stafford Disaster Relief and Emergency Assistance Act (the Stafford Act), (42 U.S.C. 5121, et seq., as amended).

unavailable, assessing the condition of facilities, containing hazardous materials, performing emergency repairs, and assisting with restoration of utility services if power lines or pipes are located near highways.

To the extent that these actions reduce the effect of the disruption and facilitate recovery, they may improve transportation network resilience. For example, the responsibilities of the Ohio DOT in the event of an emergency include assessing transportation infrastructure, coordinating with federal and local transportation agencies to prioritize missions, supporting the transportation of state emergency personnel, establishing staging areas, procuring equipment from private contractors as needed, and providing updates on the status of transportation access to the emergency site. The Ohio EOP also contains an aviation support plan and an Ohio Strategic National Stockpile Transportation Plan if medical supplies are needed (State of Ohio, 2008). The goal of these activities is to support evacuation and recovery and to restore quickly transportation services. Successfully executed, these actions can reduce the magnitude of the disruption by limiting the time that transport services are unavailable, and can facilitate response and recovery, improving resilience.

In addition, many state DOTs have internal EOPs to guide their responses with respect to highway operations in the event of an emergency. A recent NCHRP-sponsored study (PB, 2002) gives examples of specific items that might be included in a state DOT EOP: operations center plans; resource management plans for communications, equipment, and facilities; traffic management plans for evacuation and incident management; and hazard-specific plans. These actions may be able to speed the response of the DOT to the disruption, potentially reducing the magnitude of the disruption to the transport system.

Because of the wide range of actions and organizations that would be involved in responding to a disruption, proper inter-agency coordination has the potential to speed response and limit the magnitude of the disruption. The Alabama DOT reported that it annually conducts a two-day exercise to test its hurricane evacuation plan. It also participates in exercises conducted by the Alabama emergency management agency, including several at nuclear power plants. The Oregon DOT participates in an Oregon Domestic Preparedness Working Group, the Oregon InfraGard chapter (a public-private partnership led by the FBI that shares intelligence about potential threats to critical infrastructure among members), and the Regional Maritime Security Coalition. It supports two other state agencies with emergency response: receiving, storing, and distributing medicine from the national stockpile for the health department; and providing equipment and technical assistance for urban search and rescue missions for the fire service. It also participates in inter-state exercises with Washington and Idaho, and with DHS preparedness exercises (AASHTO, 2007). To the extent that these activities improve preparedness as intended they can also improve resilience when events involve disruptions to transportation infrastructure.

DOTs also address short-term transportation network needs in their daily operation of the transportation system. For example, with respect to recurring congestion, DOTs assist in relieving bottlenecks and improving signal timing (FHWA, 2008). When performing maintenance, DOTs design and implement detours and alternative routes. These and related activities of DOTs provide a solid foundation built of real-world data that can be applied in the event of a significant disruption to speed response and recovery, improving resilience.

5.3 Traffic Management Centers and Intelligent Transportation Systems

Many regions maintain traffic management centers (TMCs)[6] that monitor traffic flows and respond to traffic incidents. In most cases, they are operated by a state agency- a district office of the state DOT or a toll road authority. A minority of TMCs are operated by city DOTs. A 2003 survey identified 87 TMCs with a primary focus on freeway traffic management (SAIC, 2003). To the extent that these centers are able to use their systems to help improve the allocation of system

[6] TMCs are also known as transportation management centers.

resources by dispatching response units and redirecting traffic during disruptions, in coordination with DOTs and other agencies, they may help improve resilience.

The collection and use of real-time data by traffic management centers is an example of Intelligent Transportation Systems (ITS), which apply advanced technologies to improve the performance of infrastructure and vehicles, with the goal of enhancing safety and efficiency. Applications of ITS include the integrated management of multimodal transportation corridors, a system for forecasting the effects of weather on transportation systems, traveler information systems, support for emergency operations, and collision avoidance systems (RITA, 2009). Component technologies of ITS include ramp metering and real-time signal optimization (FHWA, 2008). Congestion pricing systems, automatic tolling, and infrastructure monitoring can also be thought of as broader components of an intelligent transportation system. Further applications of ITS are thought to be likely given the need to more actively manage flows through highly utilized transportation system, potentially through variable tolling (NYS MPO, 2005a).

Some institutional barriers will need to be overcome to ensure that the data and performance measures are incorporated effectively into response and recovery operations. For example, the ability of TMCs to coordinate effectively with emergency management agencies varies. Co-location of TMCs and emergency management agencies has been proposed as a means of improving this coordination. A 2003 survey found that 65 percent are located in exclusive transportation office space, while 35 percent include some type of shared space, most commonly with public safety and/or emergency management agencies (SAIC, 2003). There has been increasing interest in co-locating TMCs with emergency management agencies, although in many cases the TMCs and emergency management agencies are not aware of each other's role, and the potential benefits and costs of co-location have not been investigated (Hedden and Witzke, 2002). Ultimately, better information sharing and collaborative management are the goal. To the extent that co-location with other agencies allows for more effective sharing and use of real-time system data, the better that DOTs and emergency responders will be able to respond to a disruption. This observation holds in general for the effective use of data collected by ITS (FHWA, 2008).

5.4 Metropolitan Planning Organizations play an important role in transportation system planning and improvement

Metropolitan planning organizations (MPOs) are regional bodies that plan and program transportation projects.[7] MPOs are required by federal law to be formed in any urbanized area having a population over 50,000; currently, the United States has several hundred MPOs. They vary from fairly small organizations within a single county to large organizations that cross state boundaries, depending on the size of the metropolitan area. For example, Florida, with a number of small cities, has over 25 MPOs, many within a single county. The Philadelphia MPO, the Delaware Valley Regional Planning Commission (DVRPC), has members two states- Pennsylvania and Delaware. With a few exceptions, the boards of MPOs consist of locally elected (both city and county) officials. MPOs can improve the resilience of transportation systems by including some of the conditions that lead to improved resilience, as listed in Exhibit 6, when planning system improvements and extensions.

The main function of MPOs is to coordinate transportation plans and investments within a region, both of which have long-term effects on the resilience of the regional transportation network. MPOs are responsible for producing two regional transportation planning documents: the long-range transportation plan (LRTP) and the transportation improvement program (TIP). Both the LRTP and the TIP are developed with the input of one or more technical and/or citizen committees. The LRTP is a strategic document, while the TIP is tactical.

[7] In the parlance of transportation planning, "planning" means identifying both long-term goals and specific projects to realize those goals; "programming" is assigning funding to projects.

The LRTP states the region's long-term transportation priorities and goals, looking 20 years or more into the future and is typically constrained in the sense that proposed projects need to implementable within agency budgets. For example, the MPO for the San Francisco Bay Area, the Metropolitan Transportation Commission (MTC), released in late 2008 its draft *Transportation 2035: Change in Motion* long-range plan. This document presents a strategy for investing $218 billion in transportation-related projects over 25 years, including major initiatives such as road use pricing, a campaign to curb greenhouse gas emissions, major transit expansions, and a program to maximize existing highway capacity. LRTPs are updated regularly: MTC's previous 2030 plan had been formally adopted in 2005 (MTC, 2008b). In current practice, LRTPs address the long-term regional transport needs without necessarily considering the transportation network's resilience. However, these plans may benefit from explicit consideration of how the system can provide appropriate adaptive capacity and how agencies can reallocate resources when a disruption occurs.

The TIP specifies transportation projects that are to receive funding for a short term, generally ranging from three to six years. It therefore plays a role in determining short-term network resilience. The TIP must include all projects funded with federal dollars or subject to federal review (for example, if they require an environmental impact statement under the National Environmental Policy Act), and often, it includes state and locally funded, and private or public-private projects. Projects in the TIP may be proposed by the cities and counties within the MPO's jurisdiction, transit agencies, state and local highway departments, airport and port authorities, and other transportation operators. For example, the MTC's 2009 TIP contains over 1,000 individual projects totaling $12.8 billion. These projects range from purchasing paratransit vans to repaving park-and-ride lots to expanding road and bicycle trails (MTC, 2008a).

To help themselves to meet these obligations, MPOs are responsible for maintaining a regional travel demand model to estimate current travel demand and the effects of likely future growth and proposed changes to the transportation system. MPO planning efforts cover a broad range of issues spanning transportation, land use planning, and economic development and seek to satisfy multiple public goals. A review by a Transportation Research Board (TRB) committee found that the models in most common use are inadequate for many of the functions that they are now called on to perform (TRB Special Report 288, 2007). In general, transportation-planning models in use by MPOs are based on a framework developed in the 1950s to support the planning, sizing, location and construction of highways and to guide major capital investments in transportation. These models typically estimate total person trips throughout a region for a future date and assign these trips to the transportation network. Larger MPOs that have transit systems in their regions use models that also include mode choices and forecast trips by purpose and time of day (VHB, 2007)[8]. The TRB committee concluded that most models being used by MPOs are adequate for predicting aggregate demand at the level of the transportation corridor. These models are inadequate, however, for predicting traffic speeds or volumes as they fluctuate over time, the behavior of individual users of the transportation system, and goods movement (Special Report 288, 2007). MPOs frequently update their models, often with survey data: the Southern California Association of Governments (SCAG), the MPO for the Los Angeles region, last conducted a travel survey in 2000, after previously conducting surveys in 1960, 1967, 1976, and 1991 (NuStats, 2003). In order to better assess the impact of transportation system improvements on resilience, MPOs could consider enhancing the structure and modeling approach to reflect dynamic variations in traffic speeds and volumes (VHB, 2007).

As organizations, MPOs are not designed to respond to disruptions to transportation systems, such as the failure of a bridge; this is the responsibility of emergency response agencies and DOTs. A workshop of New York State MPOs concluded that MPOs can improve the performance of the transportation system by taking into account during the planning process those likely short term requirements on the system that would be required in the event of a disruption, and the long term trends that the system must accommodate (NYS MPO, 2005b). To assist in meeting these objectives, transportation demand models should be able to assess how transportation flows change over time and as a result of disruptions, and indicate the effect of temporarily reallocating system resources. Thus, given the widespread need, U.S.

[8] However, the model choices reflected in these models are relevant to passenger transportation and do not necessarily reflect the mode choices available to freight transportation.

DOT investment in developing this type of modeling capability would be beneficial to MPOs interested in assessing the affects of planning strategies on system resilience.

While MPOs are supposed to consider freight issues within their planning and programming processes, there is no clear guidance on exactly how to achieve this, or any sanction for not doing so. The most recent transportation authorization bill, SAFETEA-LU, calls for state DOTs and MPOs to "Increase the accessibility and mobility of people and freight" and "Enhance the integration and connectivity of the transportation system, across and between modes, for people and freight." (CFR Title 23, Volume I, Part 450, Sec. 450-306). However, data sources on freight movements tend to be proprietary, and the needs of goods movement are not well understood in the context of system planning.

Transport issues specific to goods movement, therefore, tend not to receive detailed attention at the MPO level, but some notable exceptions exist. Some MPOs actively incorporate freight into transportation planning and programming. For example, the Delaware Valley Regional Planning Council (DVRPC) has two full-time staff that work on freight issues, and a Goods Movement Task Force, which comprises representatives from manufacturers, freight transport firms, ports and economic development agencies that has met quarterly since 1992. DVRPC has conducted several special studies and plans about freight (e.g. *Delaware County Highway-Railroad Grade Crossing Study*, *Truck and Bus Travel in the Delaware Valley Region*, and the *Delaware Valley Rail Freight Plan*). Their 2030 long-range plan includes a separate chapter on freight, which lays out policies, strategies, and desired projects (DVRPC, 2009). The purpose of these activities is to ensure that goods movement receives appropriate attention during transportation planning activities.

Including freight transportation into planning efforts requires partnering with the private-sector shippers and carriers in a region. The Capital District Transportation Committee (CDTC), the Albany, New York Region's MPO, convenes quarterly a Goods Movement Task Force comprised of planners, shippers, carriers, academics, and analysts to exchange information regarding the needs of the goods movement community. These meetings inform the key planning documents of the CDTC (CDTC, 2007). Another example is the Atlanta Regional Commission (ARC), whose 2008 *Atlanta Regional Freight Mobility Plan* won an award for outstanding technical merit from the Association of Metropolitan Planning Organizations. The ARC's Freight Mobility Plan was the result of detailed analysis of the role of goods movement in the regional economy and collaboration with the goods movement community. The goal of the Freight Mobility Plan is to improve goods movement, while minimizing effects such as noise, congestion, and environmental effects that result from freight movements (ARC, 2008). The experience gained can help to improve system resilience in the sense that key relationships among the public and private sectors are established, and the value of goods movement to the regional economy is better understood.

These examples are exceptions for several reasons. First, freight is not simply a regional or state activity; major freight corridors usually span several states and MPOs may feel that they are not the best forum in which to address potentially broader issues. Second, MPOs do not routinely collect data on freight movements the way they collect data about passenger travel. This is because data regarding freight movements are typically proprietary. Finally, among MPOs, there may be a perception that the majority of freight is through traffic, and system improvements directed at goods movement would not benefit local residents (FHWA, 2000).

Analyzing freight in detail requires the collection of significant amounts of additional data and learning about private sector freight management. When the ARC decided to produce the *Atlanta Regional Freight Mobility Plan*, it collected several types of field data: roadside surveys of truck drivers regarding origins and destinations; and surveys and interviews with stakeholders (carriers, shippers, receivers, and logistics providers) to identify bottlenecks in the transport system and specific operating issues such as temporal patterns in shipping, costs, issues associated with the placement of facilities, and supply chain management.[9] The ARC also purchased commercial data on commodity flow for the 20-

[9] The Atlanta Regional Council maintains a website to promote the freight mobility plan. See http://www.atlantaregional.com/freightmobility/ (as of February 25, 2009).

county study area. None of these data are quickly or cheaply available. As a result of their research and analysis, the Atlanta MPOs's freight report found that 60 percent of freight movements have local origins or destinations (Wilbur Smith and Associates, 2006). Once there is a deep understanding of the day-to-day needs for goods movement in a community, then there is a knowledge base on which needs during system disruptions can be addressed. Such knowledge can facilitate planning activities specifically to improve the resilience of the system.

Several MPOs in the state of Washington are involved in planning that is related to the concept of resilience presented here. In the Seattle area, the Puget Sound Regional Council is a member of the Puget Sound Regional Catastrophic Planning Team. This group is developing, among other items, a *Regional Transportation Recovery Plan*, which will "identify likely system disruptions; [and] prioritize route restoration needs (Seattle, 2009)" The Thurston Regional Planning Council, in Olympia, Washington, is also embarking on a Transportation Recovery Plan based on its experience with a major flood in 2007. Its goal will be to "improve transportation resiliency, support system redundancy, and promote economic recovery in the event of a severe natural or man-made event (Black, 2009)." The goals of the *Transportation Recovery Plan* are consistent with our formulation of resilience as illustrated in Figures 2 and 3: successful execution of this plan could improve performance of the transport system during recovery by including some redundancies (i.e. adaptive capacity), and shortening the time of recovery.

5.5 MPOs and DOTs both contribute to building a resilient freight transportation system and collaboration is essential

Departments of Transportation, and other local, state, and federal agencies, improve the resilience of the transportation system through effective response to disruptions, and by facilitating response and recovery by other agencies. Those response and recovery activities require active management of system resources to make up for lost capacity after a disruption. However, DOTs' ability to improve resilience is limited by the resources the transportation system provides. MPOs, on the other hand, cannot react to short-term system needs, but can engage in planning that provides a system capable of responding to disruptions and accommodating long-term needs. Moreover, by sharing operational data, DOTs can provide additional support to the planning process.

Departments of Transportation contribute to transportation system resilience by minimizing the impact of a disruption and shortening the recovery time. For example, prompt action by a DOT in response to a disruption can alert travelers, preemptively reroute traffic, execute contingency plans, and begin the process of system reconstruction. All of these actions may be able to lower the peak of the curve in Exhibit 3. After the disruption, the DOT would most likely be responsible for devising a plan for system repair that meets passenger and freight transportation demands during the recovery period. A DOT may accomplish this by rerouting traffic, performing repairs at off-peak hours, or encouraging the use of alternative modes for certain trips or certain types of freight, if the resources are available. These actions actively allocate adaptive capacity to reduce the performance degradation of the system while repairs are being completed. Finally, the more quickly the affected parts of the system are returned to service, the more resilient the system. Along these lines, the California DOT, Caltrans, fosters resilience by offering contractors substantial bonuses if they return roads to service early, structuring the contracts specifically to consider separately the work performed and the time to perform it.

While DOTs are the principal organizations that respond to and address transport system disruptions, there are a number of complementary organizations that may be part of the response. Initially, DOTs may execute duties in collaboration with emergency management agencies. Traffic management centers, by using their traffic observing systems, may be able to detect quickly a disruption, and measure the effects of the disruption throughout the network, providing essential feedback on the success of the DOT's response activities. Intelligent Transportation Systems may also provide key data facilitating the response and recovery efforts.

MPOs are responsible for long term and short term system planning and improvement, complementing the activities of DOTs and other organizations. MPOs may improve resilience by promoting redundancy and structural flexibility. They do this by minimizing the impact on system performance during the period of recovery, as illustrated for the uncongested system in Exhibit 5. By taking into account the possible effects of disruptions and how they affect the system's use of resources, MPOs can ensure that the system has the adaptive capacity to provide transport services throughout the period of a disruption.

Of course, such planning should include inputs from DOTs and emergency response agencies: If long-term planning and transportation-system design are to explicitly take into account operations in the face of disruptions, then involving the responders in the planning process is essential. A series of Federal Highway Administration (FHWA) guides advocate deeper connections among the operations and planning departments of DOTs, and the observations are readily extended to include DOTs and MPOs (FHWA, 2007, 2008). Motivating the concept of regional transportation operations is the observation that the challenges faced by transportation planners and operators are becoming more dynamic and that operational considerations need to play a larger role in the planning process. Five key areas of collaboration have been identified: performance measures, data, and analysis tools; considering operations in transportation plans; institutional coordination; regional considerations; and regulation and policy (FHWA, 2008). The hoped for result of these collaborations is that the complete range of strategies can be considered for improving the performance of the transportation system and incorporated into long-term and short-term plans.

One example of how MPOs could better plan for resilience and DOTs could better plan response activities is if they had the ability to build and operate models that represent the dynamic properties of the transport systems they oversee. Although MPOs maintain transport models for their regions, these models often do not account for the dynamic behavior of the system and its individual users with respect to goods movement (Special Report 288, 2007). Incorporating operational data and lessons into these models and analytical tools could result from better linking of transportation operations and planning (FHWA, 2008).

Some recent analyses have extended traditional approaches to transportation system modeling by incorporating some aspects of resilience. In general, a traditional analysis of transportation systems characterizes the system as a network, and each link on the network has a "cost" or penalty associated with using it. The penalty may be represented as a function of the distance, travel time, probability of incurring a delay, and capacity of the link among other variables. The demand is represented by a collection of origin-destination pairs. The flows on the network are those that satisfy the demand at lowest cost. Morlok and Chang (2004) use this as a basis from which to build their approach to characterizing system robustness. The general approach to analyzing the effect of changes to the network is to specify a change to the demand or to the network, recalculate the equilibrium flow, and determine the change in "cost". Scott et al. (2006) take this approach in the calculation of the "network robustness criterion". By comparing the performance of the disrupted system to the nominal system, it is possible to assess the ability of the system to respond to the disruption. However, all of these approaches are steady state flow models that are solved for the equilibrium flow through the network. They are not capable as yet of assessing the dynamic nature of resilience as illustrated in Figures 2 and 3.

Resilience is dynamic and depends on how efficiently the network can respond to the disruption and reallocate resources. A quick response to the disruption and reallocation of resources may reduce the magnitude of the disruption. Together, MPOs and DOTs could improve their understanding of these phenomena and guide their planning and response through modeling, simulation, and innovative use of existing data and experience. However, this task is likely to be difficult. Although there are theoretical studies on the dynamic properties of traffic flows (see for example, Bando, 1995, and Orosz and Stepan, 2006), those studies assume idealized models of traffic flows, so extending them to a real transportation system would be difficult.

Therefore, there is a need to build and maintain models of regional transport systems that can be employed to assess the dynamic effects of disruptions to assist response and recovery activities. However, the data required to develop and refine these models is not yet available (Special Report 288, 2007). To address this need, analysts might begin by examining the data that is currently collected by TMCs and ITSs. Congestion and crashes occur frequently. Observing how mounting congestion along one link affects the flows of traffic on other links may indicate the effects of a larger disruption. Performance metrics representing network-wide effects of minor disturbances, and the effectiveness of response and recovery could be formulated and tested based on these observations, too. A complementary approach is to work closely with major system users and operators to develop plans explicitly designed to improve the response to disasters and prioritize system operations during emergencies and reconstruction (MIT, 2008). Collaboration with the goods movement community is especially important because data regarding their needs and likely actions in the face of a disruption are likely proprietary.

6. RECOMMENDATIONS FOR DOTS AND MPOS TO IMPROVE TRANSPORTATION SYSTEM RESILIENCE

In this section, we recommend near-term steps DOTs and MPOs can take to improve the resilience of transportation systems, especially in the context of freight transportation. In general, these actions seek to maintain transportation system services during a disruption, or alternatively, minimize the magnitude and duration of the disruption.

DOTs and their supporting agencies can improve resilience by taking the following steps:

Plan for disruptions. Since disruptions are sudden events, appropriate planning and practice of responses to disruptions is essential. Such planning would include all activities that take place in response to disruptions, including: closing roads and rerouting traffic, having suppliers and contractors in place to assist quickly in the repair of any damage to the transportation system. Coordinating with regional ports, carriers, and shippers regarding their continuity plans and how the DOT response may integrate is also critical.

Build capacity to manage system resources actively. A disruption may significantly degrade key links in a regional transportation system, but if the DOT manages its system resources to minimize the impact, the system will be more resilient. The goal of such management should be to maximize overall network performance. Assisting responses to disturbances using systems to limit network demand, such as real-time congestion pricing systems, may be an important part of the response to disruptions. Doing this may require incorporating real-time data from ITSs.

Take advantage of small-scale disturbances to prepare for larger disruptions. Transportation networks frequently experience small scale disturbances such as automobile and truck crashes on highways and train derailments on railroads. Increasingly these incidents are the cause of non-recurring congestion in heavily utilized transportation systems. These incidents vary significantly in their severity, but in general have short-term effects on the performance of the network. DOTs can use these incidents to practice certain aspects of their response activities to larger disruptions. Other opportunities for practice include network management during scheduled repairs and upgrades.

MPOs can play a strategic role in ensuring that network resources can meet demand under normal conditions and during a disruption, while also accommodating future system evolution.

Develop tools to assess the dynamic performance of integrated passenger and freight transportation systems. The majority of transportation demand models predict traffic flows based on steady-state characteristics. However, resilience is a dynamic property: the disruption itself is short, the response may be a medium-length process, and system planning and improvement is a long-term process. By accounting for the dynamic aspects of passenger and freight flows through the network in their planning models, MPOs will be able to improve system resilience over the long term. To build these models, MPOs should use the data on normal operating conditions, incidents, and responses collected by regional TMCs, ITSs, and DOTs. Building these models will require a long-term effort, but it will provide substantial benefits in the form of helping planners assess the contributions that improvements make to system resilience and by allowing for more active management of network resources.

Incorporate adaptive capacity in planning. By definition, a disruption damages system resources, reducing capacity and degrading performance. A resilient system can reallocate other system resources to meet transport demand. These resources may differ from those that are affected by the disruption: At ports, on-dock rail capacity may be increased to make up for lost road capacity; and on limited access highways, nearby surface streets may have to accommodate highway demand temporarily. Predicting exactly how system resources would be marshaled in response to a disruption is difficult, but doing so is essential to system design. Again, collaboration with system operators - DOTs, ports, and the freight community - can help to identify appropriate strategies.

Explicitly include freight and passenger traffic in planning. Freight movements are not universally included in transportation planning, and the ways in which freight contributes to transport demand and system requirements is not always clear. However, in some locations, such as Los Angeles, the port complex generates a significant amount of traffic each day, with relatively predictable patterns. In other areas, freight origins and destinations may be fewer and more complex. At the very least, MPOs have an opportunity to work with businesses in their region to understand their transportation needs and plans for growth. The current partnership among the WADOT and freight providers in the region, which seeks to characterize freight transport flows in detail and how they may be facilitated during a transportation system disruption, is an example of one approach.

Finally, DOTs and MPOs must coordinate their efforts. As discussed above, their responsibilities overlap in critical areas. If a DOT is to manage actively transportation system resources to improve resilience, the resources need to be available, and assuring appropriate resources are available requires advance consideration of transportation system resilience by the MPO.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), State DOT Issues and Activities Roundtable: Meeting of the AASHTO Special Committee on Transportation Security and the National Cooperative Highway Research Program Project Panel 20-059, Irvine, California, August 2007.

Amaral, L. A. N., A. Scala, M. Barthelemy, and H. E. Stanley, "Classes of small-world networks," Proceedings of the National Academy of Sciences, Vol. 97, No. 21, October 10, 2000, pp. 11149-11152.

American Society of Civil Engineers, "2009 Report Card for America's Infrastructure," 2009. Online at http://www.asce.org/reportcard/2009/index.cfm (as of February 16).

ARC, see Atlanta Regional Commission.

ASCE, see American Society of Civil Engineers.

Atlanta Regional Commission, "Atlanta Regional Freight Mobility Plan Final Report", February 2008, online at http://www.atlantaregional.com/documents/tp_ARFMP_final_report_2-6-08.pdf (as of June 29, 2009).

Bando, M, K Hasebe, A Nakayama, A Shibata, and Y Sugiyama, "Dynamical model of traffic congestion and numerical simulation," Physical Review E, Vol. 51, No. 2, 1995, pp. 1035 - 1042.

Black, Thera, SFY 2010 Transportation Work Program Priorities. Memorandum to Thurston Regional Planning Council, Olympia, Washington: Thurston Regional Planning Council, 2009.

Bureau of Transportation Statistics, "National Transportation Statistics", Washington, D.C.: U.S. Department of Transportation, online as of June 23, 2009 at:
http://www.bts.gov/publications/national_transportation_statistics/html/table_01_66.html

Cambridge Systematics. Prime Focus, and Kevin Heanue. Integrating Freight into Transportation Planning and Project-Selection Processes. NCHRP Web-Only Document 112. Washington, DC: Transportation Research board.

Capital District Transportation Committee, "Transportation Improvement Program", July 12, 2007, available online at http://www.cdtcmpo.org/tipdoc07/tip07.pdf (as of June 29, 2009).

CDTC, see Capital District Transportation Committee.

Code of Federal Regulations. Title 23- Highways, Chapter I--Federal Highway Administration, Department Of Transportation. Part 450- Planning Assistance and Standards, Subpart C - Metropolitan Transportation Planning and Programming.

Sec. 450.306 Scope of the metropolitan transportation planning process.

Cohen, Stephen S., *Economic Impact of a West Coast Dock Shutdown*, Berkeley, Calif.: University of California, 2002.

Committee for the Determination of the State of the Practice in Metropolitan Area Travel Forecasting, Metropolitan Travel Forecasting: Current Practice and Future Directions. Special Report 288, Washington, DC: Transportation Research Board, 2007.

Cutrell, Charles, "State SEMA Response", remarks at the Proceedings Of the September 2000 Post Earthquake Highway Response And Recovery Seminar, St. Louis, Missouri, September, 2000. As of February 4, 2009: http://www.fhwa.dot.gov/modiv/sema.htm

Delaware Valley Regional Planning Commission (DVRPC), Web page Freight Planning, http://www.dvrpc.org/transportation/multimodal/freight.htm, as of January 29, 2009.

Emergency Management Assistance Compact, http://www.emacweb.org/?9

National Emergency Management Association, http://www.nemaweb.org/home.aspx

Federal Emergency Management Agency, Multi-Hazard Mitigation Planning Guidance Under The Disaster Mitigation Act of 2000, Washington, DC, updated January 2008a.

Federal Emergency Management Agency, Producing Emergency Plans: A Guide for All-Hazard Emergency Operations Planning for State, Territorial, Local, and Tribal Governments (Comprehensive Preparedness Guide (CPG) 101), Interim Version 1.0, August 1, 2008b.

Federal Highway Administration, NHS Intermodal Freight Connectors: A Report to Congress, U.S. Department of Transportation, December 2000.

Federal Highway Administration, "Regional Concept of Transportation Operations: The Blueprint for Action", U.S. Department of Transportation, June 2007.

Federal Highway Administration, "Statewide Opportunities for Linking Planning and Operations: A Primer", U.S. Department of Transportation, May 19, 2008.

FHWA, see *Federal Highway Administration.*

Hedden, Christopher and Erika Witzke, Emerging Partnerships Between Emergency Management Agencies and Transportation Management Centers, paper presented at the 9th World Congress on Intelligent Transport Systems, 2002.

"Highway truck tunnel reopens after crash," Associated Press, November 16, 2007, available online at http://www.usatoday.com/news/nation/2007-11-16-truck-pileup_N.htm (as of June 24, 2009).

Hillestad, Richard, Ben D. Van Roo, and Keenan D. Yoho, Fast Forward: Key Issues in Modernizing the U.S. Freight-Transportation System for Future Economic Growth, MG-883, Santa Monica, CA: RAND Corporation, 2009.

Houston, Nancy, Best Practices in Emergency Transportation Operations Preparedness and Response: Results of the FHWA Workshop Series, Federal Highway Administration (FHWA-HOP-07-076), December, 2006.

Houston, Nancy, Common Issues in Emergency Transportation Operations Preparedness and Response: Results of the FHWA Workshop Series, Federal Highway Administration (FHWA-HOP-07-090), February, 2007.

Iritany, Evelyn, and Marla Dickerson, "Calculating Cost of West Coast Dock Strike is a Tough Act," *Los Angeles Times*, November 26, 2002.

Johnson, David, "State DOT Response Plan", remarks at the Proceedings Of the September 2000 Post Earthquake Highway Response And Recovery Seminar, St. Louis, Missouri, September, 2000. As of February 4, 2009: http://www.fhwa.dot.gov/modiv/sdot.htm

Massachusetts Institute of Technology, Development of a State Wide Freight System Resiliency Plan, Cambridge, MA: MIT Center for Transportation and Logistics, 2008.

MIT, see Massachusetts Institute of Technology.

Nagurney, A., and Q. Qiang, "Robustness of transportation networks subject to degradable links. 68001," Europhysics Letters, Vol. 80, 2007.

New York State Association of Metropolitan Planning Organizations, “Colloquy on the Coming Transformation of Travel: Draft Products from Day One Discussions”, June 2, 2005a, online at: http://www.nysmpos.org/pdf/NYSMPO_SCI_COLLOQUY_STATEMENTS.pdf (as of June 29, 2009).

New York State Association of Metropolitan Planning Organizations, “Colloquy on the Coming Transformation of Travel: Findings and Recommendations for Metropolitan Planning”, June 3, 2005b, online at: http://www.nysmpos.org/pdf/NYSMPO_SCI_COLLOQUY_Findings.pdf (as of June 29, 2009).

Nishiguchi, Toshihiro, and Alexandre Beaudet, "Fractal Design: Self-organizing Links in Supply Chain Management," in Georg Von Krogh, Nonaka Ikujiro and Toshihiro Nishiguchi, eds., Knowledge Creation: A Source of Value, London, UK: Macmillan, 2000, pp. 199 - 230.

NuStats, Year 2000 Post-Census Regional Travel Survey: Final Report of Survey Results, report for the Southern California Association of Governments, Fall 2003.

NYS MPO, see New York State Association of Metropolitan Planning Organizations.

Orosz, Gabor, and Gabor Stepan, "Subcritical Hopf bifurcations in a car-following model with reaction-time delay," Proceedings of the Royal Society A, No. 462, March 31, 2006, pp. 2643 - 2670.

Ortiz, David, Brian Weatherford, Henry H. Willis, Myles Collins, Naveen Mandava, and Chris Ordowich, *Increasing the Capacity of Freight Transportation: U.S. and Canadian Perspectives*, CF-228-ISE, Santa Monica: California, RAND Corporation, 2007.

PB, see *Parsons Brinckerhoff.*

Parsons Brinckerhoff, “A Guide to Updating Highway Emergency Response Plans for Terrorist Incidents,” NCHRP Project 20-07/Task 151A, U.S. Department of Transportation, 2002.

PierPASS, Inc., Q&A on PierPASS Inc. and the OffPeak Program (fact sheet), revised July 22, 2008.

Research and Innovative Technology Administration, “Intelligent Transportation Systems,” U.S. Department of Transportation, 2009, online at http://www.its.dot.gov/about.htm, as of June 29, 2009.

RITA, see Research and Innovative Technology Administration.

Science Applications International Corporation (SAIC), Emergency Transportation Operations: Freeway Traffic Management Center Capabilities and Needs, prepared for the Federal Highway Administration, September 30, 2003. Available online at http://www.ops.fhwa.dot.gov/docs/eto_caps_needs/index.htm, accessed November 17, 2008.

Seattle, see Seattle Office of Emergency Management.

Seattle Office of Emergency Management, "Regional Catastrophic Preparedness Program," 2009. Online at http://www.seattle.gov/emergency/regional/ (as of March 18, 2009).

Sheffi, Yossi. The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage, Second Edition. Cambridge, MA: MIT Press, 2007.

Sorensen, Paul, Martin Wachs, Endy Y. Min, Aaron Kofner, Liisa Ecola, Mark Hanseon, Allison Yoh, Thomas Light, James Griffin. Moving Los Angeles: Short-Term Options for Improving Transportation. Santa Monica, CA: RAND Corporation, 2008.

State of Ohio, Emergency Operations Plan, 2008.

State of Washington, Washington State Enhanced Hazard Mitigation Plan, approved January 28, 2008.

TRB Special Report 288, see Committee for the Determination of the State of the Practice in Metropolitan Area Travel Forecasting.

Vanasse Hangen Brustlin, Inc., Determination of the State of the Practice in Metropolitan Area Travel Forecasting: Findings of the Surveys of Metropolitan Planning Organizations, Prepared for Committee B0090, Transportation Research Board, 2007.

VHB, see Vanasse Hangen Brustlin, Inc.

Watts, Duncan J., Small Worlds: The Dynamics of Networks between Order and Randomness, Princeton, NJ: Princeton University Press, 1999.

Weatherford, Brian A., Henry H. Willis, and David S. Ortiz, The State of U.S. Railroads: A Review of Capacity and Performance Data, Santa Monica, CA: RAND Corporation, 2008.

Wilbur Smith Associates. Atlanta Regional Freight Mobility Plan: Data Collection, Inventory and Assessment, Tech Memo #1, for the Atlanta Regional Commission, September 29, 2006.

Willis, Henry H., and David S. Ortiz, Evaluating the Security of the Global Containerized Supply Chain, TR-214, Santa Monica, CA: RAND Corporation, 2004.