Structuring a Definition of Resilience for the Freight Transportation System

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This paper summarizes a broad literature review on system resilience. After these interpretations of resilience are considered, a definition of resilience in the context of freight transportation systems is provided. The definition of resilience offered here captures the interactions between managing organizations—namely, state departments of transportation, the infrastructure, and users—which is critical considering that the freight transportation system exists to support economic activity and production. A list of properties of freight transportation system resilience is outlined. These properties of resilience can contribute to the overall ability of the freight transportation system to recover from disruptions, whether exhibited at the infrastructure, managing organization, or user dimension. This contribution provides a framework that can serve as a starting point for future research, offering a shared language that promotes a more structured conversation about freight transportation resilience.

Resilience is a commonly used, however ill-defined term in the context of freight transportation systems. By no means is resilience a new concept or a new theoretical perspective. However, not until recently has resilience emerged as an attribute of concern for businesses and their supply chains, the transportation infrastructure, state departments of transportation (DOTs), and freight transportation systems. It has become a familiar part of the contemporary discussion of freight transportation systems, yet lacks a widely accepted, standardized definition and agreed-on measures. There has been some serious consideration of resilience in freight transportation planning at the state DOT level; however, there is still a lack of adequate qualitative tools for measuring resilience (*1*). Definitions of resilience are somewhat clearer in the business supply chain context, but that is not true of freight transportation system resilience in general (*2, 3*). It is important to place emphasis on the resilience of the freight transportation system, which includes the physical and information infrastructure, infrastructure users, and infrastructure managers. A consistent framework and definition for resilience will help guide investments and behaviors to create a more resilient freight transportation system. A resilient freight transportation system is critical in a time when the economic system is highly dependent on having reliable freight transportation.

To date, assessing structural vulnerabilities of infrastructure has been the primary method of measuring infrastructure performance in light of the resilience of transportation systems (*4–6*). Beyond assessing infrastructure vulnerabilities, activity around freight transportation system resilience is also documented by efforts of state DOTs and metropolitan planning organizations to enhance their access to data, encourage more detailed and comprehensive data collection, and subsequently construct accurate multimodal freight models (*7*). Resilience hints at the sense of responsibility for the freight transportation system's managing organization to take a more active role to understand the intricate relationship between freight transportation, system infrastructure, and economic activity. A clearly structured definition of resilience will support state DOTs' emerging interest in freight transportation system resilience.

RELATED APPLICATIONS OF RESILIENCE

Supply Chains

Resilience and freight transportation systems have been addressed in the literature in the context of supply chains through the idea of "enablers" and "strategies" of resilience. Enablers "allow an enterprise to improve resilience" and include concepts such as flexibility and communication. Strategies "are specific actions that can have a measurable impact on an enterprise's ability to tolerate disruptions" that are "used to reduce the occurrence or mitigate the effects of disruptions, allowing a supply chain to maintain or return to normal operating conditions" (*8*, p. 8). Pitera provides a framework to assess the resilience of enterprises' supply chains, which incorporates the supply chains' routine exposure to disruptions, perceptions of resilience and risk, and the actual supply chain resilience strategies employed by the enterprise (*8*). Her work on corporate resilience strategies provides some insight into the resilience strategies of freight transportation system users, and although not directly addressed here, it is of major importance to overall freight transportation system resilience. For instance, the decision of a trucking company to cancel a route in its shipment plan equates to fewer trucks on the road and less demand for roadway capacity, which alters the state of the system and influences the impact of management decisions on the network's performance. Disseminating information about system performance, therefore, improves system performance.

Enterprises

Resilience has also been studied in the organizational, or enterprise, context in which it is commonly, however not solely, attributed to the presence and engagement of good communication within and between enterprises, or private business organizations. In the example of private businesses, good communication strategies that are

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diverse, flexible, and adaptable support overall corporate resilience (*9*). Pitera further reinforces the contributions of good communication strategies to corporate resilience as a strategy for disseminating timely and accurate information (*8*). Beyond good communication, Sheffi provides qualitative analyses of select companies that highlight strategies to build flexibility into private organizations to enhance their resilience. For example, informal networks based on personal relationships, leadership at all levels, distributed power, and a general obsession with results characterize Dell Computers at the organizational level in supporting its ability to be flexible and absorb unanticipated disruptions in its supply chains (*9*).

Infrastructure

In addition to organizational resilience, studies have related resilience to the physical infrastructure. Here, resilience is defined as the timely ability of the infrastructure to absorb surges in traffic demand and recover from disruptions. Transportation infrastructure resilience has been measured primarily in a general transportation system context to understand vulnerabilities in transportation networks and therefore guide investment in transportation infrastructure to fortify against disruptions and improve recovery after a major natural or man-induced disaster (*10–14*). Methods that have emerged center on assessing the availability of alternate routing, reduction in total delay, adaptive use of high-occupancy vehicle lanes, and ability to transfer travel demand to other non-single-occupancy vehicle modes to free highway and roadway capacity to maintain freight mobility (*10*).

Disaster Research

Disaster research has also touched on the broad intersection of resilience and freight transportation. For more than 7 years, researchers with the Multidisciplinary Center for Earthquake Engineering Research (MCEER) have focused attention on conceptualizing and measuring disaster resilience. MCEER defines disaster resilience as "the ability of social units . . . to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters" (*15,* p. 15). Resilience in disaster research therefore concerns actions that contribute to social units' resilience before the disaster, during the disaster, and after the disaster to reduce the probabilities of failure, the consequences of failure, and the time for recovery. Disaster research generally falls into four defined categories of action: mitigation, preparedness, response, and recovery, each of which corresponds to a time period either pre-, during, or postdisruption (*16*). A specific resilience strategy could therefore be targeted to reduce the probabilities of failure, the consequences of failure, or the time for recovery.

The concept of a "resilience triangle," which "represents the loss of functionality from damage and disruption," emerges from disaster research (*15*). The resilience triangle helps in visualizing the magnitude of the impacts of a disruption on the infrastructure. The depth of the triangle shows the severity of damage, and the length of the triangle shows the time to recovery. The resilience triangle does not capture the probability of the disruption occurring. Figure 1 shows the resilience triangle for a 50% loss in infrastructure functionality. The smaller the triangle, the more resilient is the system. Actions, behaviors, and properties of social units, organizations, and networks all contribute to reducing the area of the resilience triangle.

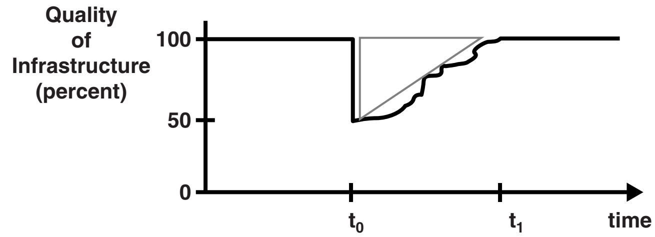

FIGURE 1 Resilience triangle (*14*).

Bruneau and colleagues' frequently published and cited article on seismic disaster and community resilience research defines resilience as "the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects" (*17,* p. 735). The authors suggest a quantification of a resilient system that incorporates "reduced failure probabilities, reduced consequences from failures, and reduced time to recovery," alluding to the importance of recognizing the analytical difference between resilience of a system before, during, and after a disruption (*17*). Furthermore, resilience suggests concurrence of "apparent opposites such as redundancy and efficiency, diversity and interdependence, strength and flexibility, autonomy and collaboration, and planning and adaptability" to explicate the complex nature of resilience and highlight the potential for confusion around current applications of resilience (*2*). In constructing a definition for freight transportation system resilience, the nuance offered by disaster research is a reminder that a specific combination of strategies can promote resilience, yet the same strategies may be in competition if engaged independently and in isolation.

DEFINING RESILIENCE

The ability for the system to absorb impacts from a disruption and continue moving traffic in an uninhibited manner is one definition of freight transportation system resilience. This simple definition is the derivation of a dictionary definition of resilience, which defines resilience as "an ability to recover from or adjust easily to misfortune or change" (*18*). From this simple definition, resilience is tied to elements of flexibility, elasticity, and an ability to recover after some disturbance. This everyday interpretation of resilience is an effective guiding principle; however, in defining resilience to measure system performance, the concept must be deconstructed into meaningfully measurable components. Although the intent of this paper is not to introduce another measurement of roadway performance, the potential for using resilience to supplement roadway performance measurement exists and is worth brief mention. First, resilience could be an assessment end point for roadway performance measurement by articulating a focal boundary. Currently discussed methods of measuring roadway performance (e.g., reliability, travel time, travel speed, vehicle counts) then become the measurement end points for resilience. In this way, resilience is the collection of roadway performance measurement end points. If a standardized and uniformly agreed-on definition of resilience can be established, a resilience factor for measuring roadway performance may be useful as an organizing principle for measuring and assessing roadway performance.

Drawing the discussion back to constructing a definition, this section will provide a definition of resilience for freight transportation systems that is the result of the extensive literature review on resilience and includes the three dimensions of the freight transportation system—physical infrastructure, users, and organizational dimensions. The physical infrastructure consists of the network of nodes and links (e.g., port facilities, distribution centers, warehouses, intermodal yards, bridges, rail lines, and roadways) that support freight transportation and travel, including the information infrastructure embedded in these facilities or located in fixed locations near them. The users include all organizations and individuals that use the infrastructure to transport people and goods. The managing organization is the unit that oversees the construction, maintenance, and performance of the infrastructure. The focus of this paper is on the transportation of goods, given the emerging interest in freight transportation system planning. It must also be recognized that the decisions of users or business entities do affect the overall system resilience through their actions.

DEFINING RESILIENCE FOR FREIGHT TRANSPORTATION SYSTEM

A structured definition of freight transportation system resilience recognizes that resilience of the freight transportation system falls on the physical infrastructure, users, and managing organization dimensions. For the purposes of this discussion, freight transportation system resilience is defined as the ability for the system to absorb the consequences of disruptions to reduce the impacts of disruptions and maintain freight mobility. Resilience hints at the sense of responsibility for the managing organization that is associated with recovery and readiness. Part of the system's ability to absorb shocks and disruptions is related to the capacity for resilience in the physical infrastructure, the preparedness of its users, and the capacity of the managing organization to respond, engage resources, and prioritize the use of limited infrastructure. There is an intricate relationship between the three dimensions of the freight transportation system that is tied to the process of recovery from major disasters. For instance, major disasters create disruptions that entail long-term planning time frames dictated by the repair or replacement of debilitated infrastructure and the reliance of many sectors of a community on usable transportation infrastructure to bring goods to market, support employment, and enable the conveniences of modern life.

Resilience at Infrastructure Dimension

Traditionally, transportation systems have been identified by their infrastructure components, although there are other major dimensions that make up the functioning of a transportation system, such as the users of that system and the managing organization. The physical infrastructure is a fundamental piece of the freight transportation system. It provides the network on which goods travel and contribute to economic activity. Resilience on this dimension is the ability of the network, given its capacity to supply lane miles, to facilitate the movement of goods under capacity-constrained conditions that are due to a disruption such as the inaccessibility of a road or a bridge. In addition, the infrastructure itself contains the capacity for resilience in its design and quality of its structures. Resilience on this dimension is achieved through sufficient infrastructure and transportation network robustness (*17*). Given its static nature, the innate characteristics of infrastructure offer one level of resilience; however, it can contribute to greater freight transportation system resilience when its capacity is properly managed.

Resilience at User Dimension

Although freight transportation system users are not generally responsible for promoting the system's resilience, individual enterprises' actions can affect system performance and, therefore, a system's ability to move goods and return to a satisfactory level of performance after a disruption. For an enterprise to successfully and efficiently move goods, government agencies must provide infrastructure, and for government agencies to provide satisfactory service on that infrastructure, enterprises must behave in a way that supports system function. For example, trucks must secure open loads and observe height restrictions as a means of avoiding disruptions. In addition, during congested periods, system performance can improve if vehicles reroute or reschedule. Interactions between individual enterprises and the system's managing organization are necessary for either to achieve resilience. Governmental agency policies and the status of the physical infrastructure are precursors to the resilience of enterprises. Often, a government's response to disruptions can have an impact on the enterprise greater than the disruption itself. With regard to both large-scale and daily disruptions, the policies of the federal, state, and local governments affect an enterprise's ability to move goods. These policies include federal policies, such as the Customs-Trade Partnership against Terrorism and the Container Security Initiative, and local policies, such as hazard mitigation plans (*1*). To be prepared for a number of potential disruption scenarios, enterprises that have the ability to disseminate information quickly, delay decision making, postpone shipments, and alter the path of the supply chain by calling on alternate suppliers facilitate the resilience of the freight transportation system. Freight transportation system resilience is a product of the dynamic interaction between organizational entities, user enterprises, and the physical infrastructure. The effectiveness of resilience at the user dimension contributes to overall system resilience to the extent that system users and the system managers are well connected with dependable and trustworthy channels of communication and fortified relationships before the onset of a disruption.

Resilience at Managing Organization Dimension

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

One organizational resilience strategy includes effective communication within the managing organization and between the managing organization and other organizations involved in transportation system management (e.g., the highway patrol). Timely dissemination of accurate information about the system's status underlies not only the organization's ability to be responsive, flexible, and adaptable, but also the overall freight transportation system's resilience. The managing organization's resilience contributes to the overall resilience of the freight transportation system, which suggests that properties of resilience at the organizational level should, therefore, include properties that can quantify actions and behaviors that promote information sharing and support quality and timeliness of information and the successful external dissemination of information. In other words, rapidity of the managing organization, and "the capacity to meet priorities and achieve goals in a timely manner in order to contain losses," are the desired outcome of organizational resilience (*17*).

The performance of both levels of the freight transportation system will greatly affect the freight transportation system's resilience; therefore, a framework for defining freight transportation system resilience offers the opportunity to begin a systematic assessment of system resilience to guide freight transportation systems planning, infrastructure investments, and program investments. Table 1 makes resilience explicit in the context of freight transportation systems and the different dimensions of the freight transportation system.

Resilience Pre-, During, and Postdisruption

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

Many actions and behaviors that promote resilience are most applicable to predisruption strategies or mitigation efforts. Mitigation describes actions and behaviors that are taken before any disruption that help curb the impact of the consequences from the disruption (*16*). Examples of mitigation efforts in the infrastructure dimension include the seismic retrofitting of bridges and overpasses or the investment in retaining walls; at the organizational dimension, fortification strategies include prioritizing freight system users in anticipation of limited infrastructure capacity and establishing processes for efficient information sharing with freight users so they can independently make appropriate decisions about how to best use available infrastructure capacity. Washington State DOT is one of the few state DOTs to pursue the study of freight system resilience planning and has recently published its report on resilience planning (*19*).

The actions and behaviors taken by users and organizations during the disruption (i.e., response) and after (i.e., recovery) also affect freight transportation system resilience. Typically these are actions or behaviors engaged in by the organization or users; infrastructure changes take longer to implement. Rapid dissemination of information concerning the disruption and reallocation of repair crews to address the disruption are examples of actions that can be taken during and after the disruption to improve resilience (*20, 21*). To choose the appropriate resilience strategy, a state DOT must evaluate the effectiveness of resilience strategies to affect capacity reductions or aid in the reconstruction of damaged infrastructure and the resumption of traffic.

PROPERTIES OF RESILIENCE

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

In regard to resilience for complex systems, Foster offers a starting point for identifying the essential properties. He identifies 31 properties of resilience for complex systems from which metrics may eventually be developed (*21*). Specific to the freight transportation system, six properties of resilience are drawn from the reviewed literature: redundancy, autonomy of components, collaboration, efficiency, adaptability, and interdependence (*11–13, 22–24*). These six properties of resilience, which were consistently mentioned across the transportation literature as critical properties, support a freight transportation system with the ability to absorb shocks and maintain adequate freight flows. Of Foster's 31 properties, these correspond to the capacity to satisfy several goals and objectives, diversity of components, functional redundancy, rapidity, efficiency, and incremental operation. Defining these properties of freight transportation system resilience establishes the detail required for a meaningful definition of resilience. A cursory introduction of these six properties is found in Table 2. The definitions shed light on each property's applicability to freight transportation system resilience.

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

The framework, expressed in Table 3, finds structure from the three dimensions of the freight transportation system, the physical infrastructure, system users, and managing organization. Properties

TABLE 1 Concept Definitions for Freight Transportation System Resilience

Concept	Definition
Resilience	"Ability to recover from or adjust easily to misfortune or change" (*17*)
Physical infrastructure	System of network of nodes and links (e.g., port facilities, distribution centers, warehouses, intermodal yards, bridges, rail lines, and roadways) and embedded sensors that support freight transportation and travel
System users	Business enterprises that move goods on the transportation infrastructure and utilize roadway information
Managing organization	Unit that oversees the construction, maintenance, and performance of the freight transportation physical infrastructure. This includes the management, utilization, and dissemination of roadway data.

TABLE 2 Concept Definitions for Properties of Freight Transportation System Resilience

Concept	Definition
Infrastructure resilience	Ability of the network to move goods in the face of infrastructure failure, either through a reduction in capacity, a complete failure, or a failure in the information infrastructure to provide information
Enterprise resilience	Ability of an enterprise to move goods in a timely and efficient manner in the face of infrastructure disruption
Managing organization resilience	"Capacity to meet priorities and achieve goals in a timely and efficient manner in order to contain losses" (*16*)
Freight transportation system resilience	Ability for the freight transportation system to absorb shocks and reduce the consequences of disruptions Freight transportation system resilience can be deconstructed along its component dimensions: the infrastructure, the managing organization, and the system users
Resilience strategies	Actions or behaviors of users or managing organizations that promote resilience in one or a number of dimensions of the freight transportation system.

of resilience are then attributed along these three dimensions. The framework also defines the contribution of each property of resilience to freight transportation system resilience along the system's three dimensions. Table 4 summarizes each of the properties of resilience along each of the three dimensions of the freight transportation system.

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

SUMMARY

This paper summarizes a broad literature review on system resilience. After these interpretations of resilience were considered, a definition of resilience in the context of freight transportation systems was developed. The definition of resilience offered here captures the interactions between managing organizations, the infrastructure, and users, which is critical considering that the freight transportation system exists to support economic activity and production. The temporal aspect of system resilience was also considered in this definition of resilience, and the resilience triangle was explored as a tool for visualizing the consequences of a disruption. Last, a list of properties of freight transportation system resilience was outlined. These properties of resilience can contribute to the overall ability of the freight transportation system to better respond and recover from disruptions at the managing organization, infrastructure, or user dimensions.

Combined, these contributions provide a framework through which a more structured conversation about freight transportation resilience can take place. This framework assists in strategic planning discussions, a precursor to investment decisions and resource allocation, to

TABLE 3 Concept Definitions for Resilience and Freight Transportation System

Concept	Definition
Redundancy	Availability of more than one resource to provide a system function
Autonomous components	Parts of a system that have the ability to operate independently
Collaboration	Engagement of stakeholders and users in a freight transportation system to promote interaction, share ideas, build trust, and establish routine communication
Efficiency	Optimization of input against output
Adaptability	System flexibility and a capacity for learning from past experiences
Interdependence	Connectedness of components of a system or the dimensions of a system, including the network of relationships across components of a system, across dimensions of a system, and between components and dimensions
Property of resilience	A subfeature of resilience that can be narrowly defined and can encompass strategies that promote a system's resilience. Properties of resilience are applicable to dimensions independent of the other dimensions and independent of other properties. Properties of resilience may appear to suggest strategies that are in opposition if applied in isolation; however, with a systematic and holistic application, property-specific strategies will yield overall benefits to a system's resilience (*1*).

TABLE 4 Six Properties of Resilience for Freight Transportation System

	Examples of Applications of Resilience			
Property[a]	Physical Infrastructure Dimension[b]	Managing Organization Dimension[b]	User Dimension[b]	Contribution to Freight Transportation System Resilience
Redundancy[c]	Availability of multiple and alternate routing options	Multiple information sources and points of delivery	Multiple parts and materials suppliers; information backed up on distributed servers	Promotes flexibility; supports robustness
Autonomy of components	Ability of highway system to function when air space closed; independent signal controls for each intersection	Independence of functional units in an organization, e.g., approvals and decision making can be independent of established hierarchies	Independence of functional units in an enterprise, e.g., procurement, billing, manufacturing, and distribution	Supports system operability despite the failure of individual system components; supports robustness
Collaboration	[Not applicable at the infrastructure dimension]	Good internal communication across divisions and external communication with system users; leadership across all levels of the organization	Public–private partnerships to build relationships between organizations[e]	Supports innovative problem solving, reduces miscommunications, spreads risk across groups
Efficiency	Network designs that reduce travel time between origin and destination	Use of effective mechanisms to prioritize spending within the organization and on infrastructure	Coordination across the supply chain with relationships built across the different parties[e]	Allows resources to be spent on activities or projects that provide most benefit to the users
Adaptability[d]	Designed with short life-spans and the intent for regular replacement; ability to assume diversity functions (e.g., adaptable-use HOV lanes)	Familiarity of roles and responsibilities across levels of the organization; cross-trained employees; leadership can be engaged at all levels	Ability to postpone decision making and shipping; build-to-order business model[e]	Promotes flexibility and system efficiency; supports robustness
Interdependence	Seamless mode transfers; intermodal facilities	Relationships are established across separate, but related agencies and within agencies; mutual understanding of the value and benefit from interaction	Standardization of parts and interchangeability[e]	Exhibits smooth connections and transitions across parts of the system; promotes system efficiency; spreads risk across the system to reduce risk

[a]The six properties adapted from Murray-Tuite (*23*).
[b]Examples of the property of resilience; not comprehensive or exhaustive.
[c]Further mentioned in Shooman (*24*).
[d]Further mentioned in Litman (*22*).
[e]Sheffi (*9*).

enhance freight transportation system resilience and performance. With a structured framework to understand resilience, managing organizations, such as state DOTs, will have the needed information to assess and classify specific actions and behaviors related to the relevant properties of resilience and ultimately improve freight transportation system resilience. The exact strategies undertaken by a managing organization will depend on the risks faced, the existing state of the system, the available resources, and the extent of the system under consideration.

Being able to identify and then understand the component properties of the nebulous concept of resilience and the association of those properties across the three dimensions of the freight transportation system, state DOTs will be well positioned to meet their responsibility of managing freight mobility and supporting regional economic activity.

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