Review of Performance Metrics for Community-Based Planning for Resilience of the Transportation System

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Community resilience depends on the resilience of the lifeline infrastructure and the performance of the disaster-related functions of local governments. State and federal resilience plans and guidelines acknowledge the importance of the transportation system as a critical lifeline in planning for community resilience and in helping local governments to set recovery goals. However, a widely accepted definition of the resilience of the transportation system and a structure for its measurement are not available. This paper provides a literature review that summarizes the metrics used to assess the resilience of the transportation system and a categorization of the assessment approaches at three levels of analysis (the asset, network, and systems levels). Furthermore, this paper ties these metrics to relevant dimensions of community resilience. This work addresses a key first step required to enhance the efficiency of planning related to transportation system resilience by providing (*a*) a standard terminology with which efforts to enhance the resilience of the transportation system can be developed, (*b*) an approach to organize planning and research efforts related to the resilience of the transportation system, and (*c*) identification of the gaps in measurement of the performance of the resilience of the transportation system.

The transportation system plays a central role in disaster management and has received a large amount of attention from federal, state, and local governments in recent years. At the federal level, the U.S. National Infrastructure Protection Plan directs the U.S. Department of Homeland Security, together with the U.S. Department of Transportation, to integrate and coordinate the overall protection of the transportation system. During fiscal years 2011 and 2013, the Transportation Security Administration and the U.S. Coast Guard conducted at least 3,438 assessments of the vulnerability of critical infrastructure (*1*). Simultaneously, $14.732 billion in federal funds was used to support disaster relief and recovery through transportation disaster-related programs (*2*).

This increased attention by the federal government has led to increases in funding for research on the resilience of the transportation system. In 2015, the National Science Foundation invested $20 million to enhance the resilience of the transportation system, among other critical parts of the infrastructure (*3*). Furthermore, federal funds have supported the development of tools for assessment of the vulnerability assets on the basis of risk analysis, such as that described in *Surface Transportation Security,* Volume 15. *Costing Asset Protection: An All Hazards Guide for Transportation Agencies* (*4*).

At the state level, the resilience of the transportation system has been a main concern of state governments with an active role in resilience planning, such as those of the states of California, Washington, and Oregon. These states have adopted a performance-based approach that addresses objectives related to the rapidity of recovery of the transportation system from disruptions. These objectives are commonly derived by expert judgment, as in the case of the Oregon Resilience Plan (*5*).

At the community level, measurement of the performance of the transportation infrastructure is therefore a key aspect of the resilience of communities because efficient resilience planning requires communities to agree on goals and measurable objectives that are sensitive to their needs. In this sense, the transportation system can be seen as the link between the built environment and the key functions and services provided by a community, such as health, education, and business (*6*).

Measurement of the performance of the transportation system in disasters has been the focus of a number of studies, which have considered conceptual frameworks, resilience metrics, and strategies. For instance, Ta et al. were the first to define resilience for the freight transportation system, which includes the physical and information infrastructure and infrastructure users and managers (*7*). In addition, the resilience of the freight transportation system has six relevant properties: redundancy, the autonomy of the components, collaboration, efficiency, adaptability, and interdependence (*7*). Furthermore, a comprehensive review by Faturechi and Miller-Hooks showed that different types of metrics for the performance of the transportation system have been used to develop strategies that enhance resilience before and after a disaster (*8*).

However, to the best of the authors' knowledge, no previous study has reviewed the modeling rationale for the existing approaches or carefully looked into their application to community resilience. Such a review is especially important because current resilience planning guides urge local governments to track the progress of the social and economic aspects of community resilience and improvement activities, although they provide little actionable guidance on how to achieve it.

The objective of this paper is to advance this research by conducting a review of the literature on methods used to assess the performance of the transportation system in disasters. The literature review was based on relevant academic papers and case studies and used the following keywords: "resilience," "freight transportation,"

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"public transportation," "public transit," "transportation," "passenger," "perception," and "economic." The Scopus abstract and citation database, the *Transportation Research Record: Journal of the Transportation Research Board* database, and their search mechanisms were used. In addition, some state and federal government resilience plans were also included by the application of typical methods used to search reviews. The measurement approaches reviewed are classified into three levels of analysis: the asset, network, and systems levels. Furthermore, this paper ties these metrics to relevant dimensions of community resilience: the technical, organizational, economic, and social dimensions (*9*). This step helps to enhance the efficiency of actions related to the resilience of the transportation system, as it provides (*a*) a standard terminology with which efforts to enhance the resilience of the transportation system can be developed, (*b*) an approach to organize planning and research efforts related to the resilience of the transportation system, and (*c*) identification of the gaps in measurement of the performance of the resilience of the transportation system.

The next section describes two major steps required to achieve any improvement of the resilience of the transportation system: assessment of resilience and disaster management. A literature review on assessment of the resilience of the transportation system is then provided. Finally, a discussion of the performance metrics reviewed and the main conclusions are provided.

TWO-STEP PROCESS FOR IMPROVING TRANSPORTATION SYSTEM RESILIENCE

The key idea underlying measurement of the performance of the transportation system is that management is not possible without measurement. Similarly, any effort to improve the resilience of the transportation system relies on two major steps, with measurement occurring before management: (*a*) assessment of the resilience of the transportation system, which evaluates the ability of the transportation system to withstand and rapidly adapt to a disruption, and (*b*) disaster management, which evaluates competitive decisions that improve this ability.

Two studies exemplify the assessment of resilience and disaster management. Cox et al. assessed resilience after the 2005 London subway and bus bombings by evaluating the impact of the bombings on the transit system by use of a time series regression approach (*10*). That work suggested the importance of multimodality in reducing the consequences of the disruption, but the analysis did not consider scenarios with different multimodal shares. In the case of disaster management, one possible approach is that of Bocchini et al., who recommended two types of bridges based on an analysis of resilience to seismic activity by the use of structural fragility and risk calculations (*11*).

Disaster management actions can be classified on the basis of the time when they are taken relative to the time of the hazard (i.e., before or after the event) and their main objective. Figure 1 shows the sequence of possible actions related to disaster management that may be taken to enhance the resilience of the transportation system before and after a disaster and some examples (*8*). In Figure 1, accessibility is measured as the number of shortest paths, the distance from the origin to the destination, travel times, travel delay, and flow.

Mitigation strategies typically consist of strategies used before a disaster to reduce the probability of the threat or the level of its consequences. For instance, Bocchini et al. developed a mitigation strategy that reduces the loss of functionality of a bridge after a disruption through the incorporation of enhanced seismic resistance into a bridge when a new bridge is designed or when a bridge receives a retrofit or is replaced (*11*).

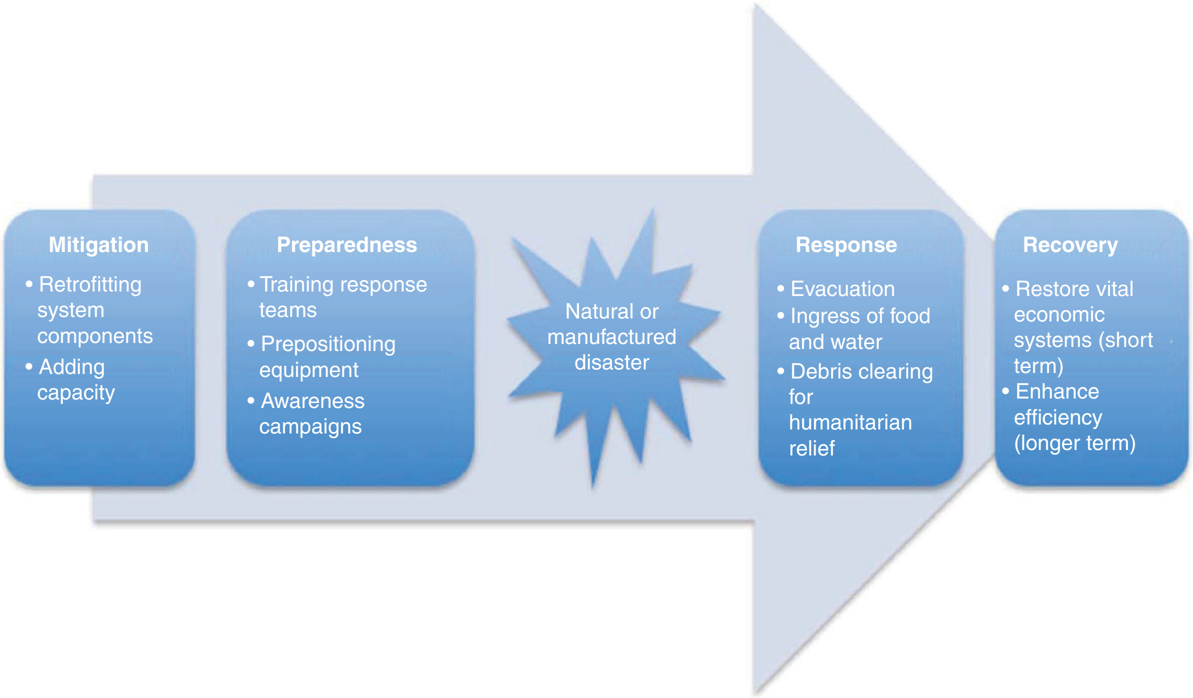

FIGURE 1 Classification of actions for and examples of management of transportation system resilience to respond to disasters.

Preparedness strategies typically aim to improve the rapidity and the efficiency of the actions taken during the response phase. In this regard, Miller-Hooks et al. used network modeling and stochastic optimization to evaluate the benefits of preparedness strategies, such as team training and equipment allocation, both to add link capacity and to provide faster and reduced-cost response activities (*12*).

After the disaster, response actions are tailored to humanitarian relief. This is exemplified by the work of Tuzun Aksu and Ozdamar, who focused on response activities to improve local access to evacuation routes and a site to temporarily dump debris by developing a debris clearance scheduling model based on network modeling and optimization (*13*).

Finally, recovery can be understood to be separate from the response phase and to consist of restoration and efficiency improvement projects. For instance, Shi et al. evaluated the effect of recovery strategies to enhance the economic resilience of various industrial sectors in Shifang, China, given a loss of the functionality of the highway sector (*14*). They used an econometric simulation model to quantify the reduction in business losses because of interruption of the businesses with different levels of substitution of inputs during the recovery phase.

The previous examples show that different approaches, such as risk analysis, network modeling, and econometric models, allow the modeling of disaster management to enhance the resilience of the transportation system. Nevertheless, the aim of the present paper is assessment of the resilience of the transportation system, given the lack of a consistent structure for measurement of the performance of the transportation system in disasters, despite its relevance as a key first step in any improvements to resilience.

CLASSIFICATION OF APPROACHES TO ASSESSMENT OF TRANSPORTATION SYSTEM RESILIENCE

Community resilience is considered the ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities that minimize social disruption while they mitigate the effects of future disasters (*9*). The development of community resilience would benefit from a structure consisting of modeling approaches and metrics for assessment of the resilience of the transportation system relevant to communities' resilience goals. In fact, transportation can be seen to be the link between the built environment and key functions and services in communities, which can be classified within the four dimensions of community resilience of Bruneau et al. (*9*):

- The technical dimension, which relates to the acceptable or desired level of performance of physical systems subjected to disruptions;
- The organizational dimension, which refers to the capacity of organizations that manage critical facilities and are responsible for the management of a disaster;
- The economic dimension, which is defined as the capacity to reduce direct and indirect economic losses from disruptions; and
- The social dimension, which refers to the capacity to reduce the negative consequences of the loss of critical services from which stricken communities and governmental jurisdictions suffer.

The performance metrics reviewed were classified according to the framework of Bruneau et al. (Figure 2) because, even though that framework is specific to resilience to seismic activity, it is one of the most widely accepted definitions of resilience (*9*). For this purpose, the technical dimension is further extended to add two broad subcategories of metrics: topological and functional metrics. The former refers to metrics that are based on the topology of the transportation infrastructure (e.g., connectivity), whereas functional metrics take into account the flow or service provided by the infrastructure (e.g., travel time). The classification used here also considers the following three different levels of analysis, depending on the level of granularity of the modeling approaches reviewed, which are further described in Table 1:

- Asset level. Analysis at the asset level considers in isolation the most basic elements of the infrastructure, such as bridges. At this level, the analysis of resilience may be useful for operators or owners of critical infrastructure who need timely, reliable, and actionable information to conduct risk management either as part of their operations or to comply with federal and state requirements.
- Network level. Analysis at the network level considers links and nodes as abstract representations of these infrastructure elements, which are studied together with the interactions between them. This approach offers the possibility to assess the resilience of either the components of the network or the whole network with the acknowledgement that critical infrastructure is not isolated and that the structure of a network also affects its resilience.
- Systems level. Analysis at the systems level evaluates various infrastructure systems and typically considers each system as a single entity but does not distinguish the components. A wider range of approaches is used for the latter scale of analysis, and their scopes vary from the quantification of some influence of a resilience metric, such as the economic impact, to the measurement of other factors that may be used to postulate the influence of the metric. The advantages of this approach depend on the scope and discipline used to analyze resilience, although in some cases this approach allows evaluation of the relationship between different systems.

Analysis at Asset Level

Performance at the asset level can be evaluated by the risk analysis approach. Some standards, such as those in *Costing Asset Protection: An All Hazards Guide for Transportation Agencies* (*4*), apply risk analysis at the asset level to assess the importance of infrastructure elements and conduct the assessment of risk under different types of threats, such as seismic risk and a terrorist attack. The following expression of risk can be found in the risk analysis literature (*25*):

$$\text{risk} = \overbrace{\begin{Bmatrix}\text{repair, replacement, etc.} \\ +\ \text{service outage}\end{Bmatrix}}^{\text{consequences}} \cdot \text{vulnerability} \cdot \text{threat} \tag{1}$$

Risk can be expressed as the product of the potential consequences of a hazard–asset pair (C); the vulnerability (V), or the likelihood that the event actually results in the estimated consequences; and the likelihood of the threat (T). Risk can be expressed in units or as a monetary value. The consequences to the asset or the enterprise involve all that directly affects the organization on a cash-forward basis, such as repair and replacement costs and the loss of revenue because of the service outage. The consequences to the public, such

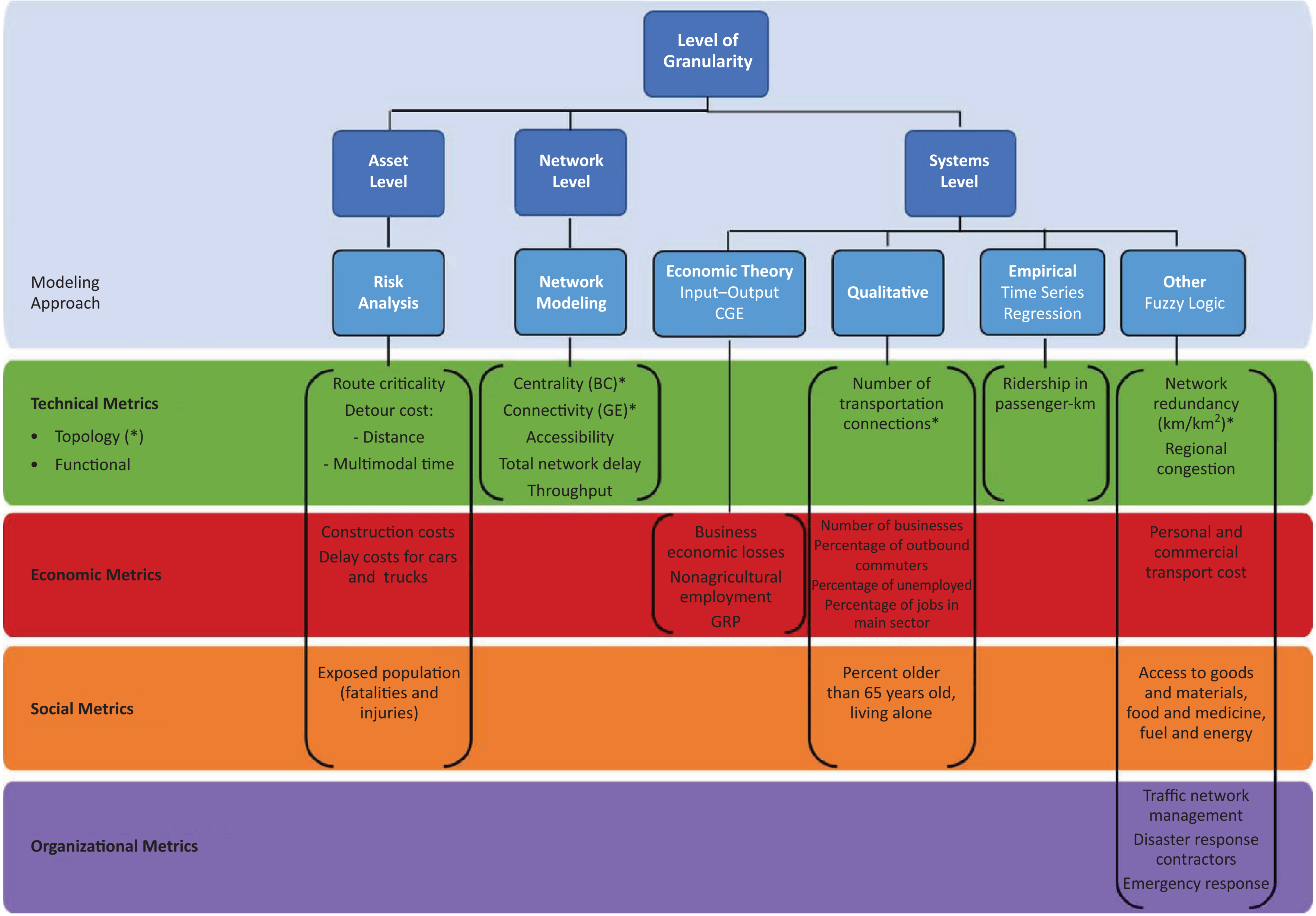

FIGURE 2 Modeling approaches to assessment of resilience and metrics per granularity level and community resilience dimension (accessibility measured in number of shortest paths, O-D distance, travel time, delay, and flow. * = metrics are related to topology of the transportation system; CGE = computable general equilibrium; GRP = gross regional product).

TABLE 1 Modeling Approaches to Assessment of Transportation System Resilience

Modeling Approach	Description
Risk analysis (*4, 11, 15*)	Estimate components of risk (i.e., threat, consequence, vulnerability) and combine them into an estimate of risk.
Network modeling and simulation (*12, 13, 16–20*)	Perform an assessment for a large number of scenarios, in some cases under evolving conditions, by the use of abstract representation of the transportation infrastructure with links and nodes.
Econometric simulation (*14, 21*)	Use economic models, such as input–output models or computable general equilibrium models for analysis of economic impact.
Qualitative (*22*)	Use text descriptions, assessments based on expert knowledge, and descriptive analysis of data or summation scales.
Empirical: time series regression (*10*)	Perform a regression analysis with time series data.
Other: fuzzy inference (*23, 24*)	Use linguistic terms (e.g., high, medium, low) and if–then rules.

as the loss of human life or the lost gross regional product, can also be included. Service outage, therefore, can be considered part of the asset-related consequences because of the threat and is normally expressed as a function of the duration of the outage and its severity (e.g., the amount of daily service denied). This component of risk has been considered independently as an indicator of asset resilience:

$$\text{asset resilience} = \overbrace{\text{duration} \cdot \text{severity}}^{\text{service outage}} \cdot \text{vulnerability} \cdot \text{threat} \tag{2}$$

However, this approach or the terminology used to address asset resilience analysis is not widely accepted, as will be described below.

Metrics for Technical Factors at Asset Level

Metrics for technical factors at the asset level can express the resilience of the critical infrastructure under the framework introduced in Equation 2. Englot developed a methodology for the assessment of resilience for the New Jersey Department of Transportation that used screening criteria for bridges and tunnels (*15*). Englot considered the general form of asset resilience to be similar to the expression in Equation 2, although vulnerability and threat likelihood were omitted (i.e., $V = T = 1$) (*15*). In this case, resilience was quantified with a metric describing the reduced functionality of the asset according to the volume of people and goods affected by its closure and the importance of the route as an emergency route (i.e., severity) during the downtime of the asset (i.e., duration). The potential delay of all transport units that had to be rerouted was considered to be aggregated over the amount of time (in days) that the bridge or tunnel was not functional (unit-hours). The automobile unit (i.e., average number of passengers of 1.2) was the transport unit used to standardize the average daily traffic of different modes (i.e., truck, railroad passenger car, rail hopper car, 100-ton rail freight car, and cargo containers). To estimate the detour travel time, different detour options were considered for each mode as a function of the detour length and the speed of travel. Furthermore, the importance of the asset as an evacuation route during emergencies was considered by use of a multiplier (with a value of 1.2). Therefore, this metric expresses resilience in terms of the multimodal detour time.

Metrics for Economic Factors at Asset Level

The risk analysis framework can also be used to estimate metrics for economic factors related to the resilience of the transportation system at the asset level. Bocchini et al. developed a method of analysis of the resiliency of bridges to seismic activity on the basis of an analysis of structural fragility and risk (*11*). In a manner different from that used by Englot (*15*), Bocchini et al. (*11*) included not only the impact of a service outage but also the construction costs (i.e., the cost to repair the structural damage) (Equation 1).

The total potential cost (i.e., risk) was estimated as a sum of the costs derived from the structural damage and the costs for users because of the detour caused by the limited functionality of the bridge (i.e., the consequences) weighted by the probability of occurrence of the event (i.e., threat) and the vulnerability to the threat.

Bocchini et al. estimated the vulnerability component of Equation 1 by analysis of the fragility of the asset (Equation 3) (*11*). In the case of estimation of the risk of structural damage, the expected value of vulnerability is the sum of expected damage states (D_d, in percent) weighted by their respective probability (P_d) across five damage states (d) (Equation 3). The five damage states are defined as no damage, slight damage, moderate damage, major damage, and complete collapse.

$$\text{risk}_{\text{structural}} = \text{consequences}_{\text{structural}} \cdot \overbrace{\left\{ \sum_{d=1}^{5} P_d \cdot D_d \right\}}^{\text{vulnerability}} \cdot \text{threat} \tag{3}$$

where $\text{risk}_{\text{structural}}$ and $\text{consequences}_{\text{structural}}$ are the risk of structural damage and the consequences of structural damage, respectively.

In the case of calculation of the cost of a service outage, Bocchini et al. used a function describing the recovery of traffic flow that models how the service outage is progressively reduced across the five damage states (d) mentioned above during the recovery of the bridge (*11*). This approach is an alternative to modeling of the disruption of the bridge as a binary state (i.e., closed or open). The recovery path [$Q(t)$] of the asset between time (t) = 0 and the duration of asset recovery (t_r) is calculated as the sum of component pairs of an expected traffic flow functionality state (Q_d, in percent) and its probability (P_d) across the five damage states at each time t of recovery (Equation 4). Therefore, the expected value of the nonfunctionality at each time t [i.e., $1 - Q(t)$] could be considered to be similar to the vulnerability component of Equation 2. The equivalent expression of asset resilience of Bocchini et al. considers the product of this vulnerability and the total potential user costs (i.e., severity) at each time t integrated across the duration of the outage and multiplied by the threat likelihood (*11*). In this case, the severity of the service outage is expressed as the detour costs of cars and trucks (in dollars). The detour costs were estimated on the basis of the average daily car and truck traffic, the detour length, the detour travel speed (30 mph), and the cost of time and distance for cars ($23/h and $0.20/mi, respectively) and for trucks ($27/h and $0.90/mi, respectively).

$$Q(t) = \sum_{d=1}^{5} P_d \cdot Q_d(t) \tag{4}$$

$$\text{asset resilience} = \left\{ \int_{t=0}^{t_r} \overbrace{\left[1 - Q(t)\right]}^{\text{vulnerability}} \cdot \text{severity} \cdot dt \right\} \cdot \text{threat} \tag{5}$$

Metrics for Social Factors at Asset Level

Finally, it is worth highlighting that risk analysis approaches have also been used to address safety concerns locally at the scale of analysis of the asset. *Costing Asset Protection: An All Hazards Guide for Transportation Agencies* also proposes a criterion that may be used to define the importance of an asset to the exposed population, which is estimated on the basis of capacity or occupancy limits (*4*). For instance, the potential number of fatalities and injuries derived from a disruption of bridges and tunnels on a road is expressed as the number of vehicles per lane distance (in feet). If the capacity of a lane is more than 2,400 vehicles, the estimate is 40 vehicles per 1,000 ft; otherwise, the capacity is 7.5 vehicles per 1,000 ft. In the case of transit or rail stations, the estimate is four times the maximum capacity of railcars.

Analysis at Network Level

The resilience literature reviewed used a network modeling approach and metrics for technical factors to assess the resilience of the transportation system by consideration of infrastructure components and their interactions. These metrics are useful for quantification of the performance of the whole network when it is subject to disruptions but also for quantification of the importance of network components on the basis of the potential consequences derived from their failure.

On the basis of the work described below, resilience at the network level can be measured by the use of topology-related metrics, such as network connectivity and component centrality, and functionality-related metrics, such as accessibility, network travel time, and throughput. King and Shalaby borrowed two metrics from the field of graph theory to assess the importance of elements of the network on the basis of topological characteristics (*20*). The betweenness–centrality (BC) measure indicates how central node (or link) v is in the network as a function of the proportion of the all-pairs shortest paths that go through that node (Equation 6). Furthermore, the general efficiency (GE) of the network is a metric of its level of connectivity. This metric is proportional to the inverse of the distance of shortest paths in the network (Equation 7).

$$\mathrm{BC}(v) = \sum_{s \neq v \neq t} \frac{d_{st}(v)}{d_{st}} \qquad (6)$$

where d_{st} is the number of shortest paths from node s to node t and $d_{st}(v)$ is the number of shortest paths from node s to node t that pass through v. BC can be normalized by the graph's number of shortest paths to range from 0 to 1.

$$\mathrm{GE} = \frac{1}{N(N-1)} \sum_{s \neq t} \frac{1}{Z_{st}} \qquad (7)$$

where Z_{st} is the length of the shortest path between node s and node t and N is the number of nodes in the network. GE is normalized by the GE of an equivalent network in which all pairs of nodes are connected.

By using simulation, King and Shalaby extended previously described graph theory concepts to develop metrics that take into account the functionality of the transit system (*20*). They defined the importance of a node as a function of the delay costs in units of time incurred in the network if that node was no longer functional. By using a congested fare-based transit assignment model, they were able to estimate the effect of congestion. Therefore, their metric takes into account the weighted average of the delays between all origin–destination (O-D) pairs by considering the O-D demand as weights. Finally, they examined the spatial nature of disruptions by looking into the average delays experienced in the origins of each geographical area (i.e., the exposure of area m) given a disruption in several nodes of the network, which is a measure of the accessibility of area m:

$$\mathrm{exposure}(m) = \frac{\sum_{k} \sum_{i \in V} \sum_{j \neq i} x_{ij} \left(c_{ij}^{k} - c_{ij}^{0} \right)}{L \sum_{i \in V} \sum_{j \neq i} x_{ij}} \qquad (8)$$

where

x_{ij} = demand from origin node i to destination node j,
c_{ij}^{k} = cost of travel from node i to node j given that node k is disrupted (c_{ij}^{0} is the base case),
L = total number of possible disruption scenarios, and
V = set of origin nodes within study area m.

Scott et al. developed the network robustness index (NRI) to assess the criticality of a link by combining topological and functional metrics (*19*). In a manner to similar that for GE introduced above, they defined the gamma index as a metric of the level of connectivity of the network. In addition, the NRI of link a measures its importance according to the total delay experienced in the network. This measure considers the rerouting of all traffic because of a failure of that link and estimates travel times with volume delay curves at each link to account for congestion (Equation 9). After the disruption of link a, the new network flows and travel times are computed on the basis of user equilibrium. Scott et al. compared the NRI values of links across networks with greater to lower levels of connectivity and quantified the worst consequences according to the congestion experienced in less connected networks (*19*).

$$\mathrm{NRI}(a) = \sum_{i \neq a} t_i x_i - c \qquad (9)$$

where

x_i = traffic flow on link i of the network without link a,
$t_i = t_i(x_i)$ = relationship between traffic flow and travel time in link i of the network without link a, and
c = systemwide travel time cost (vehicle-hours) without the removal of link a.

Miller-Hooks et al. analyzed the resilience of intermodal freight transportation by using a network approach, simulation, and stochastic optimization (*12*). They measured the performance of the network as the expected ratio of demand that can be satisfied after a disaster. That is, they estimated the total throughput of the network under several constraints, such as the constraint that the travel time between O-D pairs must not exceed 1.5 times the travel time of the shortest path between the O-D pair in the original network.

Tuzun Aksu and Ozdamar developed a model for scheduling the clearance of debris on the basis of network modeling and optimization (*13*). Their objective function considered the maximization of access from every node in the network to a set of destinations (i.e., a site for the temporary dumping of debris and the evacuation route) by clearing the blocked links after a disaster within 3 days. Access was therefore the resilience metric used, and it was defined as the number of completely cleared shortest paths (i.e., paths without blocked links) between the origin and destinations mentioned above.

The accessibility approach allows analysis of the differential impacts of disruptions in transportation networks in a geographical area. For instance, in a disrupted network the increased difficulty with the serving of the commuter flows that existed before an event between an area and the rest of the region may be a function of vehicle travel times between transportation analysis zones (*16, 17*). Similarly, the deterioration of the level of accessibility for passengers of a railway transit system after an earthquake has been modeled and documented in the literature reviewed. The latter analysis of accessibility is based on the shortest-path distance between an origin and all destinations and is weighted by the travel demand before a disaster (*17, 18*).

Analysis at Systems Level

The systems level has a wider variety of approaches than the other levels, and these approaches consider the technical, economic, social, and organizational aspects of community resilience.

Metrics for Technical Factors at Systems Level

The use of topological metrics describing the degree of connectivity and redundancy and functional metrics, such as ridership and regional parameters of congestion, has been proposed to measure resilience at the systems level.

If enough data are available, an empirical approach with ridership data may help to quantify resilience. After the 2005 London subway and bus bombings, Cox et al. analyzed the impact of a disaster on a transit system and empirically measured the resilience of the system according to passenger journeys (*10*). Specifically, their resilience metric considered the ratio of the number of lost passenger journeys avoided to the maximum possible disruption. By the use of time series regression, the maximum disruption is estimated as the reduction in the number of passenger journeys with an attack relative to a prediction of the number of passenger journeys without an attack. For this purpose, Cox et al. used the concept of direct static economic resilience (DSER) (Equation 10), which measures the extent to which the estimated percent change in direct output (percent ΔDY) deviates from the likely maximum percent change in direct output (percent ΔDY^m), where direct output is in passenger-kilometers, given an external shock (*10*). Resilience behaviors that translate into increased ridership in the alternative modes (i.e., private vehicle, cycle, motorcycle, and walking) are assumed to reduce the estimated maximum disruption.

$$\text{DSER} = \frac{\text{percent }\Delta\text{DY}^m - \text{percent }\Delta\text{DY}}{\text{percent }\Delta\text{DY}^m} \tag{10}$$

Freckleton et al. (*23*) and Urena Serulle (*24*) used the fuzzy inference approach to develop a resiliency index with 16 high-level indicators that could be classified within the technical, economic, organizational, and social dimensions of community resilience. The fuzzy inference approach acknowledges the unreliability of the information in a continuous or discrete indicator and fuzzifies its values by assigning them membership functions. Then, if–then rules are applied to combine variables into a single output. This approach was applied to evaluate topological network characteristics, such as network redundancy (i.e., the number of arterial kilometers per square kilometer).

Metrics for Economic Factors at Systems Level

At the regional level, econometric simulation models based on economic theory are useful for quantification of the economic impact of disruptions of the transportation system. Leontief first developed the input–output model as a static and linear model of purchases and sales between sectors of an economy on the basis of the technological relationships of production elements (*26*). On the basis of Leontief's input–output model (*26*), Haimes and Jiang proposed the physical input–output inoperability model for analysis of the impact of an event on various sectors of an economy, given the loss of functionality (inoperability) of some of these sectors (*27*).

$$x_i = \sum_j a_{ij} x_j + c_i \qquad \forall i \tag{11}$$

where

x_i = overall risk of inoperability of the ith infrastructure element because of a hazard,
a_{ij} = probability of inoperability that the jth infrastructure element contributes to the ith infrastructure element because of their interdependency, and
c_i = risk of inoperability inherent in the complexity of the ith infrastructure element.

Shi et al. used a computable general equilibrium model to analyze the losses of output by businesses because of the disruption of transportation on a highway in Shifang, China (*14*). In this case, a reduction in the level of access to the highway infrastructure of approximately 20% translated into an equivalent reduction in the input in the highway sector in the econometric model.

Greenberg et al. estimated the impact of major rail bridge failure by using two independent models: a model of the rail system and a simulation of the regional economy (*21*). They simulated the effect of disruptions consisting of different time delays to the passenger rail network on regional economic aspects, such as nonagricultural employment and the gross regional product. In their simulation, they assumed that the behavioral responses of users would be resilience strategies that considered that 40% of the rail users would accept a 1-h delay, 40% would drive in their autos or take buses, and 20% would telecommute.

Metrics for Social Factors at Systems Level

Greenberg et al. also assessed the negative effects of a chemical leak in a rail corridor on public health by using a plume model and estimating the number of deaths, injuries, and temporal reductions of the workforce because of exposure of the population to chemicals (*21*). The workforce is also a critical aspect of the economic resilience of a community, as segments of the workforce are essential for the continued operations of infrastructure in the aftermath of a disaster. For instance, the primary factor hindering efforts to resume transportation services in New Orleans, Louisiana, after Hurricanes Katrina and Rita in 2005 was the lack of workers (*28*).

In addition to the technical resilience of transportation system metrics, Freckleton et al. (*23*) and Urena Serulle (*24*) considered the scale of social and organizational metrics that were not considered by the previously described approaches. These metrics were access to goods, materials, fuel, and energy (i.e., the number of locations per 10 km^2) as well as food and medicine (the number of locations per 10,000 people). They evaluated organizational aspects, such as the availability of disaster response contractors, the access times of emergency response teams, and traffic network management (e.g., the direction of traffic by police officers or intelligent transportation systems).

Finally, other metrics related to the transportation system have been included in qualitative scales designed to assess the social vulnerability of communities. For instance, Chang et al. defined a hazard vulnerability similarity index (HVSI), which includes 20 items describing the economic, social, built, and natural aspects of communities (*29*). HVSI is useful for comparison of the dimensions described in two communities in a region. HVSI includes transportation aspects, such as the number of transportation connections, together with other socioeconomic items, such as the number of businesses, the percentage of the population commuting outside the community, the percentage of the population employed in the primary sector (i.e., the sector of the economy that makes direct use of or that exploits natural resources), the unemployment rate, and the proportion of the population over 65 years old living alone.

Summary of Metrics for Assessment of Resilience

The literature review described the rationale for the modeling of resilience assessment approaches at three levels of analysis (i.e., the asset, network, and systems levels). Table 2 summarizes the analytical expressions of some of these approaches to help with a comparison of their inputs.

At the asset level, the literature contains some discrepancies over whether construction and repair costs should be included in a resilience analysis. The examples discussed above quantify the consequences of a disruption to an asset not only by consideration of its functional loss (i.e., a service outage) but also by inclusion of construction and repair costs derived from the structural damage because of seismic activity (i.e., structural consequences). The inclusion of structural damage may be especially useful in the case of a cost–benefit analysis of new construction projects, as it allows a thorough evaluation of more conservative and initially more expensive solutions along the life cycle of the asset. Moreover, the expected value of vulnerability has been estimated as a function of different damage states with partial functionality but also under the assumption that the threat would lead to a complete closure of the asset during its restoration.

At the network level, metrics such as BC and GE describe important topological aspects of the resilience of networks, such as the centrality of components and network connectivity; however, functional metrics may describe more realistic aspects of network performance by considering congestion. In this regard, metrics such as the NRI of a network component and the exposure of a region consider the increased travel time given the changes to traffic flow after a disruption in the network. These metrics also assume that travel demand remains equal after the disaster. In a manner similar to that for exposure, other accessibility metrics differentiate the consequences of network disruptions across geographical areas. Some accessibility metrics express the loss of functionality only as the increased travel distance weighted by predisaster travel demand between O-D pairs.

At the systems level, scales based on fuzzy logic or qualitative scales, such as HVSI, postulate the positive effect of a wide range of indicators on community resilience. Empirical approaches with time

TABLE 2 Metrics Used for Assessment of Transportation System Resilience

Community Resilience Dimension	Asset Level	Network Level	Systems Level
Technical (topology)		$\mathrm{BC}(v)=\sum_{s\neq v\neq t}\frac{d_{st}(v)}{d_{st}}$ $\mathrm{GE}=\frac{1}{N(N-1)}\sum_{s\neq t}\frac{1}{Z_{st}}$	$\mathrm{DSER}=\frac{\text{percent }\Delta\mathrm{DY}^m-\text{percent }\Delta\mathrm{DY}}{\text{percent }\Delta\mathrm{DY}^m}$ HVSI If–then rules with fuzzy sets
Technical (functional)	$\text{asset resilience}=\overbrace{\text{duration}\cdot\text{severity}}^{\text{service outage}}\cdot\text{vulnerability}\cdot\text{threat}$	$\mathrm{NRI}(a)=\sum_{i\neq a}t_ix_i-c$ exposure (m) $=\frac{\sum_k\sum_{i\in\mathrm{v}}\sum_{j\neq i}x_{ij}\left(c_{ij}^k-c_{ij}^0\right)}{L\sum_{i\in\mathrm{v}}\sum_{j\neq i}x_{ij}}$	If–then rules with fuzzy sets
Economic	$\text{risk}=\overbrace{\begin{Bmatrix}\text{repair, replacement, etc.}\\+\text{ service outage}\cdot\text{threat}\end{Bmatrix}}^{\text{consequences}}\cdot\text{vulnerability}$		$x_i=\sum_j a_{ij}x_j+c_i \qquad \forall i$ If–then rules with fuzzy sets HVSI
Social	exposed population $=f$ (capacity of the asset)		If–then rules with fuzzy sets HVSI
Organizational			If–then rules with fuzzy sets

series regression and the application of econometric models, however, may be useful to quantify the extent of disruptions to transportation systems.

The metrics selected demonstrate either (*a*) that little documented meaningful analysis has combined individual assessments in a systemwide assessment or (*b*) that it is possible to use measures to compare systems. For (*a*), the combination of a plume model and a regional econometric model is one of the few examples of a bottom–up systemwide assessment; however, the published information is limited, and this application is context specific (*21*). For (*b*), the HVSI and network topological and functionality metrics are potentially comparable across systems, but the information provided by these metrics themselves is limited, as concluded in this paper.

DISCUSSION OF RESULTS AND CONCLUSIONS

A thorough review of the literature on measurement of the performance of the transportation system in disasters allows the authors to conclude that the assessment approaches reviewed have important implications for community resilience.

A trade-off between measurability and relevance exists when metrics are selected at different levels of granularity of the analysis. For metrics for technical factors, an analysis at the asset level allows more detail with a disaggregated estimation of detour delay (the extra travel times for all vehicles taking the detour) by different modes of transportation. At the network level, on the basis of flow-based models, a loss of accessibility may be a metric more specific than total network travel times and topological metrics. Although these metrics are more difficult to measure, such a greater level of detail may equate with metrics more relevant to the improvement of resilience. For instance, these metrics could be further developed for the design of medium- and long-term transit options especially important for populations without access to vehicles. They may also be relevant for companies that have not planned for ways to continue business after a disruption, such as through the use of flex hours and telecommuting (*30*). However, the data required for this type of risk analysis are not available, and establishment of a link between network models, land use, and vulnerable populations for assessment of the resilience of the transportation system remains a challenge. Further research is thus necessary.

Relevant metrics for economic factors to quantify the regional impact of disruptions to the transportation sector can be derived from econometric models. However, the difficulty with the running and maintenance of these models by local governments because of organizational limitations, such as financial stresses and the lack of trained workforces, must be noted (*21*).

For metrics for social and organizational factors, qualitative and fuzzy logic approaches present the opportunity to develop practical and easily measurable scales. In some cases, metrics such as the number of contractors are also highly relevant for community resilience. High-level metrics and more granular ones, such as the population exposed at the asset level, are arguably incomplete by themselves. Assessments of resilience would benefit from the combined use of both high-level and qualitative metrics with other quantitative approaches.

To build community resilience, the authors have established a need to develop practical norms of measurement of the performance of the transportation system that are based on available data and standard analyses. New measures are not necessarily required; rather, the existing measures identified in this paper could be adopted and used more consistently. In this way, the effective enhancement of resilience is feasible only if local governments work in close collaboration with higher-level governmental entities. Local governments are in the best position to identify and protect the needs of communities because of their proximity to citizens and because they operate community services. Local governments simultaneously rely on transportation agencies and state and federal governments for the application of advanced methodologies for the assessment of resilience. For instance, local governments need guidance and training on the resilience assessment tools developed by the federal government to apply for grants or comply with the law. In addition, regional econometric models or travel demand forecasting models are more likely to be maintained by dedicated transportation agencies or state governments.

The research developed in this paper is important because it facilitates collaboration between governmental entities at various levels, identifies how the different metrics describing the resilience of the transportation system can be used to achieve resilience-related objectives, and compares these metrics. This paper highlights the gap in understanding between different perspectives and metrics on assessment of the resilience of the transportation system and the importance of having representatives of each of these perspectives work closely together in any community effort to achieve resilience.

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