Measuring the Performance of Transportation Infrastructure Systems in Disasters: A Comprehensive Review

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Abstract: This paper provides a comprehensive overview of the literature on transportation infrastructure system performance in disasters. Specifically, it reviews those articles appearing in refereed journals, conference proceedings, and technical reports since the late 1990s that provide insights and tools for the assessment of anticipated transportation system performance, along with its management, given the possibility of physical damage resulting from a future hazard event. In the considered literature, performance may be gauged under characteristics of risk, vulnerability, reliability, robustness, flexibility, survivability, and resilience, the most common concepts or measures in the literature. In addition to providing an archive and synthesis of recent literature on this topic, the approximately 200 articles are classified based on a host of criteria, including applied measure (qualitative or quantitative), conceptual approach, and methodology. **DOI: 10.1061/(ASCE)IS.1943-555X.0000212.**

Author keywords: Infrastructure; Transportation networks; Risk; Reliability; Robustness; Flexibility; Survivability; Resilience.

Introduction

Transportation infrastructure systems provide a network of options to support the mobility of people and goods. They connect businesses and support supply chains and services. Moreover, they offer accessibility to vital resources for daily activities and in emergency circumstances. In this latter case, these systems play a key role in survivor evacuation, rescue operations, and community reconstruction and recovery. These systems are exposed to risk from a multiplicity of hazards, ranging from natural events and technological failures to intentional malicious acts. Disruptions in the operation of these systems can have cascading impacts within the system and on other interconnected critical lifelines. In addition to the effects of direct damage to the physical transportation infrastructure, indirect damage to, for example, the economy and social systems may result.

The frequency of disasters, whether natural or human-made, has increased to an unprecedented level in the last decade (Guha-Sapir et al. 2011). Likewise, the impacts of such events on transportation systems have intensified due to increased system complexity and interdependency, and urbanization in coastal and other disaster-prone areas. Hurricane Sandy (2012), Hurricane Irene (2011), the Japanese Tsunami (2011) and subsequent nuclear meltdown, the Sichuan Earthquake in China (2008), the Christchurch earthquake in New Zealand (2011), the Minneapolis I-35W bridge collapse (2007), and Hurricane Katrina (2005) are only a few examples of recent devastating events. Their impact illustrates how susceptible transportation systems, and their infrastructure, are in such circumstances. Damage caused by Hurricane Sandy to the New York City transportation system amounted to $7.5 billion (WABC-TV/DT 2012). Hurricane Irene affected more than 500 miles of highways, 2,000 miles of roadways, 200 miles of railways, and 300 bridges in Vermont (Lunderville 2011). The collapse of the I-35W Bridge over the Mississippi River imposed over $0.4 million in costs to daily passenger trips alone due to traffic rerouting (Zhu et al. 2011).

Transportation infrastructure systems are also a common target of terrorist attacks, such as the 9/11 attacks and the bombings in London (2005), Madrid (2004), and Mumbai (2006). In addition to the resulting physical damage, these events have long-term socioeconomic and psychological impacts. Furthermore, they affect traveler decisions. Gordon et al. (2007) identified a 6% reduction in passenger trips and a large shift from public transit services to private automobiles during a two-year period following the 9/11 attacks.

An increasing awareness of these issues has led to a growing body of literature on the subject of transportation systems performance in disaster. A marked and continued growth in journal articles, both qualitative and quantitative, on this topic followed the 1995 Kobe earthquake (also noted by Chang and Nojima 2001). The articles range in content from conceptual frameworks and performance metrics to strategies for improving preparedness and reducing the duration of time required for recovery. This paper aims to provide a comprehensive overview of that portion of this literature, which emphasizes performance evaluation in the presence of physical damage resulting from hazard impact.

The contributions of this work include (1) an archive and synthesis of recent literature on the studied topic; (2) analysis and organization of approximately 200 journal articles, conference proceedings, and technical reports based on a host of criteria, including qualitative/quantitative concepts, measure employed/defined, assessment or management strategy used, and proposed mathematical methodology; and (3) a framework for considering this body of literature, similarities and differences in their coverage, approach, and utility. An additional benefit of this review is that it provides newcomers to the field with the background needed to contribute to

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the area, and enables the identification of gaps in the literature for which additional study is warranted.

Study Scope

An enormous number of works address the performance of transportation systems, and hundreds of these works consider aspects associated with disaster events involving these systems. This subject is rather general. The scope of this paper, thus, was carefully chosen to provide insights into that portion of the literature pertaining to transportation system performance given damage to the physical infrastructure.

Articles that provide strategies for preparing for or responding to disaster events (e.g., evacuation planning, resource allocation), address humanitarian relief logistics, or focus on the effects of disaster on human well-being or the environment (e.g., air quality or ecology) are not included in this review. Additionally, studies on the material properties of transportation system components from a structural engineering perspective, such as modeling bridge fragility and road pavement cracking/distortion, are excluded. While several pioneering works from the late 1990s are included, this review primarily includes works published since 2000.

A variety of terms have been used to label events precipitating disaster. These include hazard, threat, perturbation, and disruption event. They are referred to herein as *hazards* and are considered herein to fall within one of three categories: (1) natural climatic/geological events (e.g., earthquake, hurricane, flood, and tsunami); (2) operational and technological failures due to hardware/software degradation/error and human error (e.g., major traffic accidents); and (3) intentional malicious acts, such as terrorist attacks. The term *disaster* is used to describe an event in which such a hazard has caused extensive physical damage; the event is nonrecurring and likely unanticipated, and its location, impact area, and severity cannot be predicted with certainty.

Overview of Terminology

A variety of performance metrics have been proposed in the disaster literature for evaluating and analyzing disaster impacts on transportation systems. Selection of an appropriate disaster measure for the particular application is an important first step in system analysis. These measures can be generally categorized as risk, vulnerability, reliability, robustness, flexibility (also known as agility and adaptability), survivability, and resilience. Other performance metrics, such as total travel time, throughput, economic loss, and connectivity, that may also provide input in quantification of some of these measures, are considered and categorized herein as alternative measures of effectiveness (MOEs). Because authors use these terms in a variety of ways, and also sometimes introduce new terminology for similar concepts or do not define their chosen terminology, this review includes those works using alternative terminology under the most relevant of these categories. Where an author uses a measure that might be categorized under an alternative heading, the default is to assign that work based on the terminology adopted by the author.

Risk

Risk is a concept used to characterize the threat of a disaster event in terms of its likelihood of occurrence and consequences. Thus, risk is typically measured as with respect to the probability of an event arising and its corresponding effects (e.g., Basoz and Kiremidjian 1996). Often their product is taken. These two risk components must be derived through detailed location-specific probability and impact (e.g., likelihood of structural damage of varying levels, reduction in services, and health or environmental concerns) estimation. In the context of transportation system performance in disaster, risk can be a good measure when considering engineering failures related to a specific component, such as the collapse of a bridge; it may be impractical for use in networks consisting of many components. Thus, alternative measures may be preferred (Taylor et al. 2006).

Vulnerability

Vulnerability, like risk, considers the potential consequences of a disaster event on system performance. It captures a system's weaknesses or susceptibility to threats related to operational performance (e.g., Berdica 2002; Jenelius et al. 2006). Unlike risk, however, the probability of the disaster event is not accounted for (Jenelius et al. 2006). That is, vulnerability studies recognize that it may be difficult to predict the likelihood of very rare events for many systems, and expectations that incorporate such low probability events may not be very illuminating (Taylor et al. 2006). The concept of vulnerability can be vague and is often described qualitatively.

Reliability

Reliability is typically defined as the probability that a network remains operative (often a function of connectivity) given the occurrence of a disaster or disruption event (e.g., Scaparra and Church 2008; Balakrishnan et al. 2009). Variants with utility for transportation systems have been introduced that capture effects of disruption on performance level. Such a reliability measure might be, for example, the probability of a system performing within a satisfactory level of service under a disruption event (Wakabayashi and Iida 1992). One can view reliability as the complement of vulnerability, where the former considers remaining functionality and the latter potential loss or degradation (Berdica 2002; D'Este and Taylor 2001). Concepts of reliability are used extensively in assessing telecommunication networks, electric power grids, and other engineered systems, where failures can be recurrent, and thus, their probability of occurrence may be significant and predictable.

Robustness

Robustness measures the ability of a system to continue in operation and, thus, maintain some level of functionality, even when exposed to disruption. Like reliability, it is a measure of strength rather than loss and can be seen as a complement to vulnerability (Jenelius et al. 2006; Snelder et al. 2012). For many works in the literature, robustness has been synonymous with reliability. Where they are distinguished from one another, it is that reliability considers probability of meeting a given level-of-service; whereas, robustness assesses remaining functionality for a given event. It might be noted that offering a high degree of reliability often requires a robust system. Robustness concepts have been applied to engineered systems (Nagurney and Qiang 2007), including computer systems and telecommunications, for example. In the context of transportation systems, this concept was initially applied to measure network-level impacts of node or link removal (e.g., Chang and Nojima 2001; Sakakibara et al. 2004; Scott et al. 2006; Nagurney and Qiang 2007).

Table 1. Common Definitions of Common Performance Metrics

Measure	General definition
Risk	Combination of probability of an event and its consequences in terms of system performance
Vulnerability	Susceptibility of the system to threats and incidents causing operational degradation
Reliability	Probability that a system remains operative at a satisfactory level post-disaster
Robustness	Ability to withstand or absorb disturbances and remain intact when exposed to disruptions
Flexibility	Ability to adapt and adjust to changes through contingency planning in the aftermath of disruptions
Survivability	Ability to withstand sudden disturbances to functionality while meeting original demand
Resilience	Ability to resist, absorb and adapt to disruptions and return to normal functionality

Flexibility

Another relevant concept is flexibility (also known as adaptability or agility). It captures the inherent capacity of a system to cope with uncertainty. This concept is primarily used in manufacturing systems, where for example multipurpose system elements or processes enable adaptation to new circumstances, e.g., pooling resources to allow the same capacity to be used for production of a variety of products (Morlok and Chang 2004). This concept has been applied in the transportation arena. For example, Morlok and Chang (2004) measure system flexibility in terms of the transport system's ability to continue to accommodate traffic with existing capacity under demand uncertainty. Chen and Kasikitwiwat (2011), and Tomlin (2006) (Husdal 2009) discuss flexibility with respect to supply uncertainties, e.g., possible degradation in the functionality of facilities, or other network nodes or links. Application to supply chain disaster management involves a general definition of flexibility as the ability to adapt and adjust to supply changes through contingency planning in the aftermath of disruptions. Flexibility can be viewed as the opposite of robustness, capturing the ability of the system to absorb changes with negative impact as opposed to the ability to endure these changes without adaptation (Faturechi and Miller-Hooks 2013).

Survivability

Survivability is a measure of whether or not a network can continue to perform its intended function given damage to network components (Mead et al. 2000). Morlok and Chang (2004) describe survivability as a supply-oriented concept aimed at measuring the fraction of system demand that can be met post-disruption. A main application area for survivability measures has been telecommunication networks. These networks are often partitioned hierarchically, rendering some components more important than others. Additionally, arc traversal times are considered to be trivial in comparison to time spent waiting to pass through network nodes. Thus, extension of specific survivability measures developed for this industry to transportation systems requires adaptation (Abdel-Rahim et al. 2007; Du and Peeta 2012). This measure may be comparable to robustness.

Resilience

Resilience was initially conceptualized and applied in the context of ecological systems (Holling 1973). It is generally defined as a system's ability to resist and absorb the impact of disruptions (Bruneau et al. 2003). It builds on the strengths or weaknesses measured by risk, vulnerability, reliability, robustness, and survivability (i.e., resistance) and adaptability measures, while also encapsulating the benefits of the system's ability to adapt to post-disaster circumstances as in flexibility measures. Resilience measures, thus, account for possible interventions that can aid in returning system performance to nearly pre-disaster levels. They can quantify the potential benefits of pre-disaster mitigation actions aimed at increasing the system's ability to cope with disaster impact and post-disaster adaptive actions that aim to restore functionality.

Summary

In Table 1, the most agreed upon interpretations of these measures discussed in this section are given. Fig. 1 provides a schematic of their boundaries and interactions.

Qualitative versus Quantitative Approaches to Assessing Performance

The literature on disaster-related performance measurement can be categorized by whether qualitative descriptions are given or quantitative measures are defined. Such descriptions can provide insights into impact evaluation and management tactics. Quantitative measures, on the other hand, provide direct measurement that can be used to assess or predict disaster impact. Such measures can aid in the prioritization of mitigation, preparedness, and adaptive actions.

Some quantitative measures have been implemented within software or other types of decision support tools. Table 2 provides an overview of the literature through this categorization approach, distinguishing those works in which mathematical models or quantification techniques are provided from those in which a tool employing such models or techniques is described. Mathematical models are further classified by whether they provide direct assessment or suggest decisions that can be used to alter system performance. Assessment includes component- and system-level performance, both of which allow for identification of critical system elements. The models that suggest decisions support management of these systems. Disaster management includes prioritization and optimization of pre- and post-disaster investment options with the aim of maximizing a system's coping capacity, reducing disaster losses, and/or restoring performance.

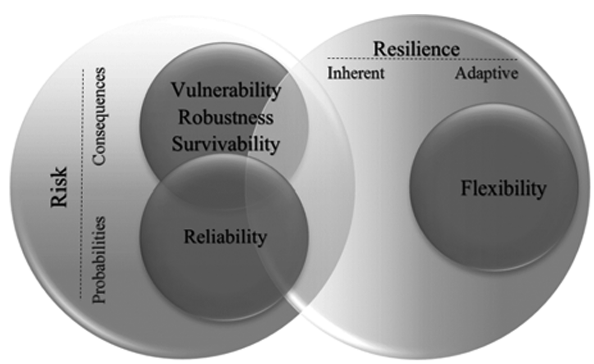

Fig. 1. Disaster measures, their boundaries and interactions

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Table 2. Qualitative and Quantitative Publications in Disaster Research

Concept	Qualitative conceptualization	Quantitative approaches: Modeling — Assessment	Quantitative approaches: Modeling — Management	Quantitative approaches: Tool development
Risk	Basoz and Kiremidjian (1996), Cafiso et al. (2005), D'Andrea et al. (2005), Haimes et al. (2002), Homeland Security (2007)	Basoz and Kiremidjian (1996), Bensi et al. (2011), Chang et al. (2010), Chang et al. (2000), Chang and Nojima (2001), Cho et al. (2001), Dalziell and Nicholson (2001), Di Gangi and Luongo (2005), Gupta (2001), Ham et al. (2005), Kim et al. (2002), Kiremidjian et al. (2007), Murray-Tuite (2007, 2008, 2010), Na and Shinozuka (2009), Shiraki et al (2007), Stergiou and Kiremidjian (2010), Tatano and Tsuchiya (2008), Wang and Elhag (2007), Werner et al. (2000)	Chang et al. (2010), Kim et al. (2008), Murray-Tuite and Fei (2010), Shinozuka et al. (2003), Zhou et al. (2004)	Banerjee and Shinozuka (2009), Dalziell and Nicholson (2001), Eguchi et al. (1997), Werner et al. (2008)
Vulnerability	Berdica (2002), Berle et al. (2011), D'Este and Taylor (2001)	Bell et al. (2008), Chen et al. (2007), D'Este and Taylor (2001), Ferber et al. (2009), Ibrahim et al. (2011), Jenelius et al. (2006), Knoop et al., (2012), Lownes et al. (2011), Luping and Dalin (2012), Luathep et al. (2011), Lu and Peng (2011), Murray-Tuite and Mahmassani (2004), Shimamoto et al. (2008), Sohn (2006), Sohn et al. (2003), Tampere et al. (2007), Taylor et al. (2006), Tu et al. (2012), Ukkusuri and Yushimito (2009), Yingfei et al. (2010)	Chang (2003), Lou and Zhang (2011), Mohaymany and Pirnazar (2007), Patidar et al. (2007), Viswanath and Peeta (2003)	Erath et al. (2008), Jenelius and Mattsson (2012), Taylor and Susilawati (2012)
Reliability	Bell (2000), Berdica (2002), Iida (1999), Nicholson and Du (1997), Nicholson (2003)	Al-Deek and Emam (2006), Andreas et al. (2008), Asakura (1999), Bell (2000), Bell and Iida (2001), Bell and Schmocker (2002), Chen et al. (2002), Chen et al. (2013), Chen and Eguchi (2003), Golroo et al. (2010), Iida (1999), Lam et al. (2008), Nicholson (2003), Sumalee and Watling (2008), Nojima (1999), Szeto (2011), Siu and Lo (2008), Wakabayashi and Iida (1992), Yin and Ieda (2001)	Augusti et al.(1998), Bin et al. (2009), Chootinan et al. (2005), Desai and Sen (2010), Dimitriou and Stathopoulos (2008), Golroo et al. (2010), Lo and Tung (2003), Lou and Zhang (2011), Sumalee and Kurauchi (2006), Poorzahedy and Bushehri (2005), Sanchez-Silva et al. (2005), Snyder and Daskin (2005), Park et al. (2007), Yin and Ieda (2002)	—
Robustness	Berdica (2002), Nagurney and Qiang (2007), Snelder et al. (2012)	Angeloudis and Fisk (2006), Derrible and Kennedy (2010), De-Los-Santos et al. (2012), Ip and Wang (2011), Moreira et al. (2009), Morohosi (2010), Nagurney and Qiang (2007,2009,2012), Snelder et al. (2012), Sakakibara et al. (2004), Sullivan et al. (2010), Scott et al. (2006)	Cappanera and Scaparra (2011), De-Los-Santos et al. (2012), Fan and Liu (2010), Faturechi et al. (2014), Huang et al. (2007), Liu et al. (2009), Laporte et al. (2010), Liberatore et al. (2011), Patriksson (2008), Santos et al. (2010), Scaparra and Church (2008, 2012), Zhang and Levinson (2004)	—
Survivability	Abdel-Rahim et al. (2007), Mead et al. (2000)	Grubesic and Murray (2006), Matisziw and Murray (2009)	Abdel-Rahim et al. (2007), Chen et al. (2011), Du and Peeta (2012), Garg and Smith (2008), Peeta et al. (2010), Smith et al. (2007)	—
Flexibility	Chen and Kasikitwiwat (2011), Morlok and Chang (2004), Tomlin (2006)	Morlok and Chang (2004), Sun et al. (2006)	Faturechi and Miller-Hooks (2013)	—
Resilience	Bruneau et al. (2003), Caplice et al. (2008), Croope and McNeil (2011), Dorbritz (2011), Goodchild et al. (2009), Mansouri et al. (2010), Ortiz et al. (2008), Reggiani (2012), Ta et al. (2009)	Bekkem et al (2011), Berche et al. (2009), Cox et al. (2011), Freckleton et al. (2012), Liu and Murray-Tuite (2008), Murray-Tuite (2006), Nguyen et al. (2011), Omer et al. (2011), Vugrin et al. (2011), Zhang et al. (2009)	Chen and Miller-Hooks (2012), Faturechi et al. (under review), Faturechi and Miller-Hooks (2013), Losada et al. (2012), Miller-Hooks et al. (2012), Vugrin et al. (2010), Vugrin and Turnquist (2012)	Adams et al. (2012), Leu et al. (2010), Nair et al. (2010), Omer et al. (2011), Serulle et al. (2011)

Categorization by Life-Cycle Phase

The disaster life cycle is often described as having four phases: mitigation, preparedness, response, and recovery (e.g., Green 2002). The first two phases arise pre-disaster, when the disaster occurrence and its component- and system-level impacts can only be anticipated and actions can be developed for their mitigation. The latter two phases involve the implementation of post-disaster adaptive actions that aim to restore system performance to pre-disaster levels.

Mitigation efforts typically aim at reducing the probability of disaster occurrence or the level of its consequences. The aim of such efforts may be to reduce the probability of an attack (e.g., human-made) on the system or reduce the likelihood that an attack will cause a given level of damage (i.e., will have certain consequences). In the context of transportation systems, the primary mitigation strategies can be described as (1) retrofitting system components, (2) expanding the system to include new links or nodes, (3) adding capacity to existing system elements, or (4) positioning resources for protective purposes. The concept of expansion as a mitigation strategy is fairly new, and its benefits are derived through added post-disaster residual capacities. Highway embankment, assignment of security teams, and bridge fortification, are some examples of mitigation strategies used to combat floods, terrorist attacks, and earthquakes, respectively.

Preparedness strategies support quicker and more efficient response in a disaster's aftermath. Such strategies might include, for example, implementing awareness campaigns, training response teams, or pre-positioning equipment and/or other resources, such as water pumps for use in floods and salt spreaders for snow or ice handling.

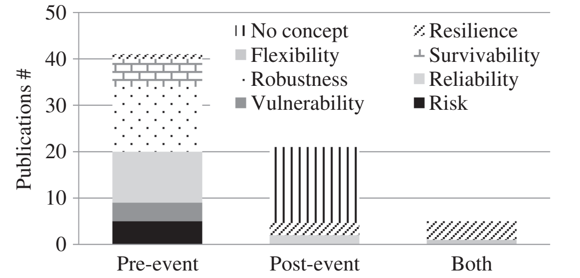

Fig. 2. Number of disaster management publications in pre- and post-disaster phases

Post-disaster emergency response includes short-term response actions in the aftermath of a disaster with the aim of restoring system performance. The first portion of this life-cycle phase is devoted to humanitarian relief operations, such as emergency rescue and medical service distribution (not covered in this study). This is followed by repair of damaged system components with the objective of restoring connectivity or increasing system throughput levels. Pavement crack repair, debris removal, and construction of temporary road mats, are some examples of response strategies.

Table 3. Summary of Disaster Management Research Based on Life-Cycle Phases

Concept	References	Mitigation: Retrofit	Mitigation: Expansion	Preparedness	Response	Recovery
Risk	Chang et al. (2010), Kim et al. (2008), Shinozuka et al. (2003), Wang et al. (2008), Zhou et al. (2004)	X	—	—	—	—
Vulnerability	Mohaymany and Pirnazar (2007), Patidar et al. (2007), Viswanath and Peeta (2003)	X	—	—	—	—
	Lou and Zhang (2011)	—	X	—	—	—
Reliability	Augusti et al. (1998), Golroo et al. (2010), Poorzahedy and Bushehri (2005)	X	—	—	—	—
	Chootinan et al. (2005), Dimitriou and Stathopoulos (2008), Lo and Tung (2003), Lou and Zhang (2011), Park et al. (2007), Yin and Ieda (2002)	—	X	—	—	—
	Sanchez-Silva et al. (2005), Snyder and Daskin (2005)	—	—	X	—	—
	Desai and Sen (2010)	X	—	X	—	—
	Bin et al. (2009), Sumalee and Kurauchi (2006)	—	—	—	X	—
Robustness	Cappanera and Scaparra (2011), Fan and Liu (2010), Liu et al. (2009), Liberatore et al. (2011), Scaparra and Church (2008, 2012)	X	—	—	—	—
	De-Los-Santos et al. (2012), Laporte et al. (2010), Patriksson (2008), Santos et al. (2010), Zhang and Levinson (2004)	—	X	—	—	—
	Huang et al. (2007)	—	—	X	—	—
	Faturechi and Miller-Hooks (2013)	X	X	X	—	—
Survivability	Du and Peeta (2012), Peeta et al. (2010)	X	—	—	—	—
	Abdel-Rahim et al. (2007), Chen et al. (2011), Garg and Smith (2008), Smith et al. (2007)	—	X	—	—	—
Flexibility	Faturechi and Miller-Hooks (2013)	—	—	X	X	
Resilience	Losada et al. (2012)	X	—	—	—	—
	Chen and Miller-Hooks (2012), Vugrin et al. (2010)	—	—	—	X	—
	Miller-Hooks et al. (2012)	X	—	X	X	—
	Faturechi et al. (under review)	—	—	X	X	—
	Vugrin and Turnquist (2012)	—	X	X	X	—
	Faturechi and Miller-Hooks (2013)	X	X	X	X	—
No specific concept	Barbarosoglu and Arda (2004), Chang (2003), Ferris and Ruszczynski (2000), Feng and Wang (2003), Karlaftis et al. (2007), Lambert and Patterson (2002), Lertworawanich (2012), Liu et al. (2008), Modarres and Zarei (2002), Yan and Shih (2009), Yan et al. (2012)	—	—	—	X	—
	Chen and Tzeng (2000), Mehlhorn (2009), Orabi et al. (2009), Sato and Ichii (1996)	—	—	—	—	X

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Table 4. Categorization of Publications Based on the Applied Performance Measure

Performance measure	Assessment	Management			
		Mitigation	Preparedness	Response	Recovery
Functional measures					
Travel time/distance	Basoz and Kiremidjian (1996), Bell (2000), Bell et al. (2008), Chang et al. (2000), Chang et al. (2010), Dalziell and Nicholson (2001), De-Los-Santos et al. (2012), Freckleton et al. (2012), Golroo et al. (2010), Ibrahim et al. (2011), Israeli and Wood (2002), Jenelius et al. (2006), Jenelius and Mattsson (2012), Kiremidjian et al. (2007), Knoop et al. (2012), Lam et al. (2008), Lownes et al. (2011), Lo and Tung (2003), Murray-Tuite (2006), Morohosi (2010), Nagurney and Qiang (2007, 2009, 2012), Omer et al. (2011), Stergiou and Kiremidjian (2010), Sumalee and Watling (2008), Suarez et al. (2005), Shimamoto et al. (2008), Shiraki et al. (2007), Szeto (2011), Siu and Lo (2008), Ukkusuri and Yushimito (2009), Werner et al. (2000), Yin and Ieda (2001), Zhang et al. (2009)	Al-Deek and Emam (2006), Cappanera and Scaparra (2011), De-Los-Santos et al. (2012), Dimitriou and Stathopoulos (2008), Fan and Liu (2010), Golroo et al. (2010), Yin and Ieda (2002), Kim et al. (2008), Laporte et al. (2010), Losada et al. (2012), Liberatore et al. (2011), Liu et al. (2009), Lou and Zhang (2011), Lo and Tung (2003), Murray-Tuite and Fei (2010), Poorzahedy and Bushehri (2005), Scaparra and Church (2008, 2012), Shinozuka et al. (2003), Yin and Park et al. (2007), Zhang and Levinson (2004), Zhou et al. (2004)	—	Ferris and Ruszczynski (2000), Feng and Wang (2003), Lambert and Patterson (2002), Liu et al. (2008), Vugrin et al. (2010), Yan and Shih (2009)	Chen and Tzeng (2000), Orabi et al. (2009), Sato and Ichii (1996)
Throughput/capacity	Adams et al. (2012), Bekkem et al (2011), Chang et al. (2010), Chen et al. (2002), Caplice et al. (2008), Chen et al. (2013), Cox et al. (2011), Liu and Murray-Tuite (2008), Luping and Dalin (2012), Morlok and Chang (2004), Murray-Tuite (2006, 2010), Na and Shinozuka (2009), Nojima (1999), Sun et al. (2006), Sohn et al. (2003), Tampere et al. (2007), Vugrin et al. (2011)	Chen et al. (2011), Chootinan et al. (2005), Desai and Sen (2010), Faturechi and Miller-Hooks (2013), Garg and Smith (2008), Kim et al. (2008), Miller-Hooks et al. (2012), Smith et al. (2007)	Desai and Sen (2010), Faturechi et al. (under review), Miller-Hooks et al. (2012), Vugrin and Turnquist (2012)	Chen and Miller-Hooks (2012), Faturechi and Miller-Hooks (2013), Faturechi et al. (under review), Karlaftis et al. (2007), Miller-Hooks et al. (2012), Sumalee and Kurauchi (2006), Vugrin and Turnquist (2012), Yan et al. (2012)	—
Accessibility	Chen et al. (2007), Chang and Nojima (2001), Chang et al. (2010), D'Este and Taylor (2001), Luathep et al. (2011), Lu and Peng (2011), Sohn (2006), Taylor and Susilawati (2012), Taylor et al. (2006)	Mohaymany and Pirnazar (2007), Santos et al. (2010), Viswanath and Peeta (2003)	Modarres and Zarei (2002), Sanchez-Silva et al. (2005)	Chang (2003)	Mehlhorn (2009)
Topological measures	Andreas et al. (2008), Angeloudis and Fisk (2006), Asakura (1999), Bell and Iida (2001), Bell and Schmocker (2002), Berche et al. (2009), Chang et al. (2010), Chen and Eguchi (2003), Di Gangi and Luongo (2005), Derrible and Kennedy (2010), Ferber et al. (2009), Grubesic and Murray (2006), Iida (1999), Ip and Wang (2011), Matisziw and Murray (2009), Moreira et al. (2009), Murray-Tuite and Mahmassani (2004), Morohosi (2010), Sakakibara et al. (2004), Snelder et al. (2012), Sullivan et al. (2010), Scott et al. (2006), Tu et al. (2012), Wakabayashi and Iida (1992), Yingfei et al. (2010), Zhang et al. (2009)	Augusti et al. (1998), Balakrishnan et al. (2009), Du and Peeta (2012), Kim et al. (2008), Peeta et al. (2010)	—	Bin et al. (2009), Lertworawanich (2012)	—

Table 4. (*Continued.*)

Performance measure	Assessment	Management			
		Mitigation	Preparedness	Response	Recovery
Economic measures	Bensi et al. (2011), Cho et al. (2001), Dalziell and Nicholson (2001), Eguchi et al. (1997), Gupta (2001), Haimes et al. (2002), Ham et al. (2005), Kim et al. (2002), Na and Shinozuka (2009), Tatano and Tsuchiya (2008), Werner et al. (2000, 2008)	—	—	—	—

Recovery, as the final phase of the disaster life cycle, continues beyond emergency response, until actions to improve system performance are terminated. This phase may take months, even years, to accomplish; thus, requiring long-term planning. Short-term decisions taken in the response phase can impact the efficiency of the recovery phase (Baird 2010).

The reviewed literature is categorized by life-cycle phase and performance measure in Table 3. As illustrated in the histogram of Fig. 2, reliability and robustness are common pre-disaster measures used in the literature, while most studies on post-disaster response and recovery do not involve any specific disaster measure. Furthermore, system resilience is the one measure chosen by the majority of studies to model both pre- and post-disaster actions simultaneously.

Categorization by MOEs

A variety of user- and supply-oriented MOEs have been developed in the literature. These differ depending on the transportation mode, such as intermodal ports, airports, highway networks and transit services, for which they were developed, and specific system objectives.

Two major categories of MOEs were identified: function and topological. Functional measures focus on serviceability of the transportation system as categorized by: travel time/distance, flow or throughput, and accessibility. Topological measures consider the transportation system as a pure network and characterize it based on concepts of graph theory. Measures such as connectivity, betweenness, and centrality fall into this category. These measures focus on the relative location of network nodes and links and their interconnections rather than operations.

In addition to functional and topological MOEs, a number of studies have been conducted on the estimation of economic losses due to disaster damage within transportation systems. However, it appears that no work in the literature presents or discusses quantitative economic measures for disaster management purposes.

Table 4 summarizes the literature by these three categories of MOEs: functional, topological and economic. The histograms in Figs. 3 and 4 provide a graphical representation of the number of publications that falling under these categories. The figures indicate that travel time is the most utilized MOE. In the context of recovery, it is the predominant measure. Topological measures have been applied primarily in mitigation and response studies.

Categorization by Uncertainty Modeling Technique

The geographic location, severity and other impacts of a disaster event can at best be known *a priori* with uncertainty. Several

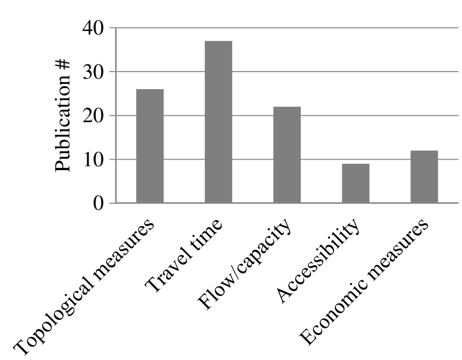

Fig. 3. Number of disaster assessment publications on each MOE

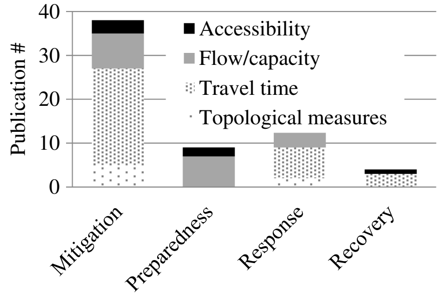

Fig. 4. Number of disaster management publications on each MOE and life-cycle phase

different approaches have been applied within this literature for modeling possible disasters and their consequences. Such models are employed in providing input for system optimization and analysis. These approaches can be generally categorized as falling under scenario, simulation, probability distribution, and worst-case performance-based techniques as given in Table 5. This table also includes those works that study a single historical disaster event.

Scenario-based techniques generate one or more hypothetical disaster scenarios; the probability of the scenario's occurrence is not regarded. Applications of these techniques generally consider a small set of component-level scenarios, e.g., failure of a road segment or a bridge. Before and after analysis are often conducted for comparison. Techniques that include targeted and coordinated attack scenarios aiming at the most important system components also fall in this category. Simulation techniques generate a wide range of scenarios for consideration. The scenarios are generated in proportion to the disruption or damage occurrence probabilities at the component level. A distribution of system performance level over all considered scenarios can be generated. Other techniques that employ disruption or damage probability occurrences might use the probability distribution functions directly. Finally, optimization and game-theoretic modeling approaches, e.g., interdiction models, can be used to identify a worst-case performance that might results from damage to the system, where the damage may be given in terms of, for example, a number of link failures.

Categorization by Methodology

Mathematical models of system performance, for either assessment or management purposes, proposed in the literature can be considered as analytical, simulation, or optimization models. Those that address assessment are described in Table 6, while others addressing management are given in Table 7.

Analytical methods have been used to analyze potential failure states and risk classification based on disaster probabilities and consequences through different forms of logical structures, e.g., risk matrix, event tree analysis (ETA), fault tree analysis (FTA), and failure mode and effects analysis (FMEA). In disaster management, analytical models, specifically analytical hierarchy process (AHP), have been applied for evaluating, ranking, and prioritizing decision options through concepts of utility theory. These methods are not efficient for large-scale applications with a large number of possible failure states and candidate investment options (Wang et al. 2008; Murray-Tuite 2008).

Simulation methods, such as Monte Carlo simulation, are employed to generate a large sample of scenarios, each with a randomly selected damage state and probability of occurrence. These methods broadly allow generation of different combinations of degradation in the links or nodes. Simulation methods are also employed to evaluate the effectiveness of investment options by comparing system performance before and after expenditures are made. Such evaluation is made separately for an individual scenario; thus, related decisions may be suboptimal under other arising scenarios.

Table 5. Categorizing by Disaster Event Modeling Technique

Uncertainty modeling techniques	References
Scenario	Al-Deek and Emam (2006), Basoz and Kiremidjian (1996), Bell et al. (2008), Chang et al. (2000), De-Los-Santos et al. (2012), Fan and Liu (2010), Faturechi et al. (under review), Ferber et al. (2009), Freckleton et al. (2012), Feng and Wang (2003), Golroo et al. (2010), Gupta (2001), Ham et al. (2005), Ip and Wang (2011), Jenelius et al. (2006), Kim et al. (2002), Kiremidjian et al. (2007), Knoop et al. (2012), Liu et al. (2009), Liu and Murray-Tuite (2008), Luathep et al. (2011), Luping and Dalin (2012), Lu and Peng (2011), Murray-Tuite (2006, 2007, 2010), Nagurney and Qiang (2007, 2009, 2012), Nguyen et al. (2011), Omer et al. (2011), Peeta et al. (2010), Shinozuka et al. (2003), Sohn et al. (2003), Shimamoto et al. (2008), Sumalee and Watling (2008), Sun et al. (2006), Sullivan et al. (2010), Scott et al. (2006), Tatano and Tsuchiya (2008), Taylor et al. (2006), Tu et al. (2012), Ukkusuri and Yushimito (2009), Vugrin et al. (2010, 2011), Vugrin and Turnquist (2012)
Simulation	Bell and Schmocker (2002), Bensi et al. (2011), Berche et al. (2009), Chang et al. (2010), Chang (2003), Chen et al. (2002), Chen and Miller-Hooks (2012), Cho et al. (2001), Dalziell and Nicholson (2001), Dimitriou and Stathopoulos (2008), Du and Peeta (2012), Faturechi and Miller Hooks (2013), Garg and Smith (2008), Kim et al. (2008), Miller Hooks et al. (2012), Morohosi (2010), Murray-Tuite (2008), Murray-Tuite and Fei (2010), Na and Shinozuka (2009), Nair et al. (2010), Nojima (1999), Patriksson (2008), Stergiou and Kiremidjian (2010), Shiraki et al (2007), Sumalee and Kurauchi (2006), Tampere et al. (2007), Werner et al. (2000), Zhou et al. (2004), Zhang and Levinson (2004)
Probability distribution	Andreas et al. (2008), Angeloudis and Fisk (2006), Asakura (1999), Augusti et al. (1998), Bin et al. (2009), Chen et al. (2007), Chootinan et al. (2005), Derrible and Kennedy (2010), Desai and Sen (2010), D'Este and Taylor (2001), Iida (1999), Lam et al. (2008), Moreira et al. (2009), Nicholson (2003), Park et al. (2007), Poorzahedy and Bushehri (2005), Sakakibara et al. (2004), Sanchez-Silva et al. (2005), Siu and Lo (2008), Wakabayashi and Iida (1992), Yin and Ieda (2001, 2002)
Worst-case performance	Bell (2000), Bell et al. (2008), Bell and Iida (2001), Chen et al. (2011), Cappanera and Scaparra (2011), Grubesic and Murray (2006), Huang et al. (2007), Ibrahim et al. (2011), Jenelius and Mattsson (2012), Laporte et al. (2010), Liberatore et al. (2011), Lim and Smith (2007), Lou and Zhang (2011), Losada et al. (2012), Lownes et al. (2011), Lo and Tung (2003), Matisziw and Murray (2009), Murray-Tuite and Mahmassani (2004), Scaparra and Church (2008, 2012), Smith et al. (2007), Snyder and Daskin (2005), Szeto (2011), Yan and Shih (2009), Yates and Lakshmanan (2011)
Historical scenario	Bekkem et al. (2011), Chang et al. (2000), Chang and Nojima (2001), Cox et al. (2011), Zhang et al. (2009)

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Table 6. Assessment Methodologies

Methods	References	Description
Analytical methods		
Risk matrix	Basoz and Kiremidjian (1996), FAA (2007)	Ranking risk of system components with respect to disaster probability and consequences, from low to extreme risk
ETA/FTA	Al-Deek and Emam (2006), Murray-Tuite (2007, 2008)	Representing probable states of system components using logical structures in the form of a tree
FMEA	Bekkem et al. (2011), Caplice et al. (2008)	Analyzing potential failure states and classifying risk
Fuzzy inference approach	Freckleton et al. (2012), Serulle et al. (2011), Wang and Elhag (2007)	Assessing vulnerability using linguistic terms such as High, Medium, and Low rather than precise numerical values
Input-output analysis	Cho et al. (2001), Gupta (2001), Ham et al. (2005), Kim et al. (2002), Sohn et al. (2003), Tatano and Tsuchiya (2008)	Modeling system losses, mostly economic, with respect component interconnections
Bayesian analysis	Bensi et al. (2011), Murray-Tuite (2010)	Real-time assessing of post-disaster system performance through evolving information
Simulation	Chen et al. (2002), Chen et al. (2013), Dalziell and Nicholson (2001), Kiremidjian et al. (2007), Knoop et al. (2012), Liu and Murray-Tuite (2008), Morohosi (2010), Murray-Tuite (2006), Na and Shinozuka (2009), Nojima (1999), Omer et al. (2011), Shinozuka et al. (2003), Shiraki et al (2007), Snelder et al. (2012), Suarez et al. (2005), Sumalee and Watling (2008), Tampere et al. (2007), Stergiou and Kiremidjian (2010), Vugrin et al. (2011), Werner et al. (2000)	Generating a large number of disruption scenarios, useful for capturing failure dependencies of system components
Deterministic optimization		
Graph-theoretic models	Abdel-Rahim et al. (2007), Andreas et al. (2008), Angeloudis and Fisk (2006), De-Los-Santos et al. (2012), Derrible and Kennedy (2010), Ferber et al. (2009), Ip and Wang (2011), Jenelius and Mattsson (2012), Moreira et al. (2009), Nagurney and Qiang (2007, 2009, 2012), Sakakibara et al. (2004), Scott et al. (2006), Shimamoto et al. (2008), Sullivan et al. (2010), Taylor et al. (2006), Tu et al. (2012), Yingfei et al. (2010), Wakabayashi and Iida (1992)	Determining most critical nodes/links using graph theory concepts (e.g., connectivity); scenario-based, but no event probabilities included
Game-theoretic models	Israeli and Wood (2002), Murray et al. (2007), Matisziw and Murray (2009), Ukkusuri and Yushimito (2009)	Sequentially seeking to maximize and minimize transportation costs using a two-player game between a leader and follower for identifying worst-case performance as in interdiction problems; no event probabilities included
Stochastic optimization		
Game-theoretic models	Bell (2000), Bell et al. (2008), Grubesic and Murray (2006), Ibrahim et al. (2011), Lownes et al. (2011), Murray-Tuite and Mahmassani (2004), Szeto (2011), Murray-Tuite and Fei (2010), Yates and Lakshmanan (2011)	Incorporating in the game the uncertain characteristics of the transportation network due to disasters, where the leader seeks to maximize the expectation of transportation costs
Markov chain models	Bell and Schmocker (2002), Nguyen et al. (2011)	Modeling a set of failure states assuming Markovian transitions between states
Utility-theoretic models	Asakura (1999), Chen et al. (2007), Lam et al. (2008), Luathep et al. (2011), Siu and Lo (2008), Sun et al. (2006), Yin and Ieda (2001)	Using concepts of random utility theory to model stochastic user route choice under disruptions (Stochastic user equilibrium)

Table 7. Management Methodologies

Methods	References	Description
AHP	Modarres and Zarei (2002), Patidar et al. (2007), Wang et al. (2008)	Prioritizing alternatives based on concepts of utility theory
Simulation	Chang (2003), Chen and Tzeng (2000), Sato and Ichii (1996), Zhang and Levinson (2004), Zhou et al. (2004)	Evaluating management options under a large number of scenarios
Deterministic optimization	Feng and Wang (2003), Golroo et al. (2010), Karlaftis et al. (2007), Lambert and Patterson (2002), Lertworawanich (2012), Mehlhorn (2009), Mohaymany and Pirnazar (2007), Orabi et al. (2009), Viswanath and Peeta (2003), Vugrin et al. (2010), Yan and Shih (2009), Yan et al. (2012)	Optimally selecting alternatives, e.g., resource allocation and reconstruction scheduling, regardless of event probabilities
Stochastic optimization		
Game-theoretic models	Cappanera and Scaparra (2011), Yates and Lakshmanan (2011), Laporte et al. (2010), Lou and Zhang (2011), Losada et al. (2012), Liberatore et al. (2011), Scaparra and Church (2008, 2012), Smith et al. (2007), Yates and Snyder and Daskin (2005)	Optimally selecting design alternatives under worst-case scenario through use of a multi-level defender-attacker game, where the defender makes decisions on network design in the upper–level and the attacker responds to these decisions in the lower-level
Reliability-based constrained models	Bin et al. (2009), Chootinan et al. (2005), Desai and Sen (2010), Dimitriou and Stathopoulos (2008), Lo and Tung (2003), Park et al. (2007), Poorzahedy and Bushehri (2005), Santos et al. (2010), Sanchez-Silva et al. (2005), Sumalee and Kurauchi (2006), Yin and Ieda (2002)	Optimally selecting design alternatives using stochastic network design with reliability requirements, e.g., chance constrained modeling
Multi-stage stochastic programming	Barbarosoglu and Arda (2004), Chang et al. (2010), Chen et al. (2011), Chen and Miller-Hooks (2012), Du and Peeta (2012), Fan and Liu (2010), Faturechi et al. (in review), Faturechi and Miller-Hooks (2013), Ferris and Ruszczynski (2000), Garg and Smith (2008), Kim et al. (2008), Liu et al. (2008), Liu et al. (2009), Miller-Hooks et al. (2012), Nair et al. (2010), Peeta et al. (2010), Vugrin and Turnquist (2012)	Optimizing sequence of alternative selection over time given realization of uncertain problem elements in each time stage
Robust optimization	Huang et al. (2007), Laporte et al. (2010), Patriksson (2008)	Optimally selecting alternatives to guarantee system performance under worst-case scenario; generating conservative and expensive solutions

Typical optimization models, whether deterministic or stochastic, exploit a network representation of an area and seek to optimize network performance functions such as one that maximizes flow or throughput, or makes an optimal traffic assignment. In the context of disaster assessment, these techniques are applied to evaluate disaster impacts and identify the most critical nodes or links. They can also be employed to optimally plan for pre-disaster network design or the pre-positioning of resources, and post-disaster resource allocation and response/recovery scheduling. Stochastic optimization is applied to capture the nonrecurrent and uncertain nature of disaster impacts within an optimization framework. Unlike analytical and simulation methods, stochastic optimization models are capable of providing decisions to address multiple possible future damage events, rather than simply offering separate decision strategies for separate disaster scenarios.

Conclusions and Insights

In this paper, a comprehensive review of the literature addressing transportation system performance measurement given potential future disaster events is provided. Related publications were identified and categorized from a variety of perspectives. This categorization provides clarity through direct comparison of similarities, differences, intersections, and interactions, permitting a deeper understanding of the topic. The review also aids in the identification of research challenges and gaps to be addressed in the future.

Although the literature was scoured for all transportation environments, the vast majority of the scholarly literature related to disaster performance measures and transportation has focused on surface transportation as is reflected in this literature review. The review reveals that nearly 70% of publications on this topic reported in this review address the assessment of the transportation system's ability to cope with disaster consequences. Publications including strategies for managing these systems in disaster are fewer in number, but growing. While decision makers can benefit from techniques that consider interdependency of decisions in different stages of the disaster life cycle and multiple disaster scenarios, more than 90% of disaster management publications reviewed herein address only one component of the life cycle. Although qualitative works of relevance were reviewed, much of the analysis provided herein focuses on quantitative efforts. Additional effort to categorize the qualitative studies on disaster assessment may be useful.

An uptick in papers explicitly considering uncertainty in future conditions can be noted from the review. More generally, an increase in articles that incorporate complexities of the real world, including dependencies that contribute to system-level failure, is noticeable. In that vein, an increase can be noticed in the percentage of articles that consider system- rather than component-level performance. To consider these complexities, simulation is often required. Improved computational capabilities in recent years has also made sensitivity analysis possible on a larger scale, as evidenced by the increasing number of articles employing such approaches.

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