# Resilience of Transportation Systems: Concepts and Comprehensive Review

Yaoming Zhou, Junwei Wang, and Hai Yang

*Abstract*—**Resilience of transportation systems has been extensively studied in the past decade. This paper aims to provide a synthesis of the up-to-date literature on resilient transportation, focusing on concepts and methodologies. A systematic literature search method integrating database search, related journal search, and citation supplement is proposed to select all the appropriate articles. Based on the selected core papers, the definition of resilience is examined, and some related concepts are compared. The main body of the review is devoted to the review of metrics and mathematical models used to measure resilience and the strategies used to enhance resilience. Several popular subtopics are identified and discussed. Finally, current research gaps and challenges are addressed, and some potential research directions are presented.**

***Index Terms***— **enhancement, measurement, resilience, transportation**

## I. INTRODUCTION

OUR society largely relies upon a quantity of critical infrastructure systems, such as transportation systems, water supply systems, electrical grids, communication systems, and so forth. These systems cooperate to provide essential commodities and services for our daily life. In the past decades, these systems have become more and more complex and interdependent, which makes them vulnerable to disruptions and difficult to recover. Therefore, unexpected disasters may incur dramatic human and financial toll. Transportation systems are among the most suffered infrastructure systems in disasters. Earthquake and Hurricane are the two main causes of large-scale transportation disruptions, such as Sichuan earthquake (2008), Chile earthquake (2010), Tohoku earthquake and tsunami (2011), Hurricane Katrina (2005), Hurricane Irene (2011), and Hurricane Sandy (2012). The economic damage caused by Hurricane Sandy to the New York City transportation system reached up to 7.5 billion US dollars [1]. Sichuan earthquake partially disrupted 21 highways and 5 more that were under construction. Five national roads and 11 provincial roads were severely destroyed. Since transportation networks serve as lifelines that provide access to impacted areas to support emergency response and long-term recovery operations after a disaster, the stable functionality of transportation networks means a lot from both economic and welfare perspectives.

Many concepts have been utilized to study the performance of transportation systems when they are exposed to risk from various disturbances, ranging from frequent day-to-day fluctuation to rare natural disasters, among which the term resilience has increasingly been seen in the literature. Compared with the other terms including robustness, reliability, survivability, and flexibility, resilience focuses on the performance reduction and recovery when facing inevitable disruptions. To deal with day-to-day fluctuations, a well-designed system is able to absorb the disruptions and maintain its functions. However, for large-scale disasters such as earthquakes, systems would inevitably deviate away from the equilibrium states. The ability of a system to reduce efficiently both the magnitude and duration of deviation from designed performance levels is the most significant connotation of resilience [2].

The word resilience stems from Latin word “resiliere”, which means to rebound, or spring back. After Holling [3] conceptualized resilience in the context of ecological systems and classified the distinction between resilience and stability, the concept of resilience has been introduced to different disciplines including organization [4], economics [5], social science [6], supply chain [121-123] and engineering [7, 124, 125]. Though there may be different interpretations of resilience in various areas, most of them are based on the same idea that resilience is the ability of a system to return to normal condition after disruptions which change its state [8]. Resilience has been extensively studied in transportation engineering especially in recent years. This paper seeks to expand on the prior work to provide an up-to-date comprehensive review on the concepts and methodologies in the area of resilient transportation.

The contributions of this work are derived from: (a) an archive and synthesis of up-to-date literature on resilient transportation, (b) discussion on the definition of resilience in transportation, (c) a classification scheme to discuss the metrics and mathematical models used to measure resilience and

Manuscript received Feb.1, 2018. This work was supported by the National Natural Science Foundation of China (NSFC) (Grant No. 71571156), by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. [T32-101/15-R]), by the University of Hong Kong through the Seed Fund for Basic Research (Grant No.201611159213), and by the open project funded by State Key Laboratory of Synthetical Automation for Process Industries (PAL-N201802). *(Corresponding author: Junwei Wang.)*

Y.M. Zhou and J.W. Wang are with the Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong Shenzhen Institute of Research and Innovation, Pokfulam Road, Hong Kong. (e-mail: youngme910@hku.hk, jwwang@hku.hk).

H. Yang is with the Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology (e-mail: cehyang@ust.hk).

strategies used to enhance resilience of transportation systems, (d) identification of several popular subtopics, and (e) some potential research directions.

The remainder of the paper is outlined as follows. In Section II, literature search using a novel search method is conducted, followed by categorization and analysis. In Section III, the definition of resilience in the context of transportation is discussed, accompanied by comparison with related concepts. In Section IV and V, the metrics and mathematical models used to measure resilience and strategies used to enhance resilience are reviewed respectively. In Section VI, several popular subtopics in the literature are identified, followed by potential research directions and conclusions in the last section.

## II. Literature Search and Analysis

### A. Literature Search

To give a comprehensive overview, we start our work with systematically searching for articles that focus on resilience of transportation systems. Due to the difficulty of determining

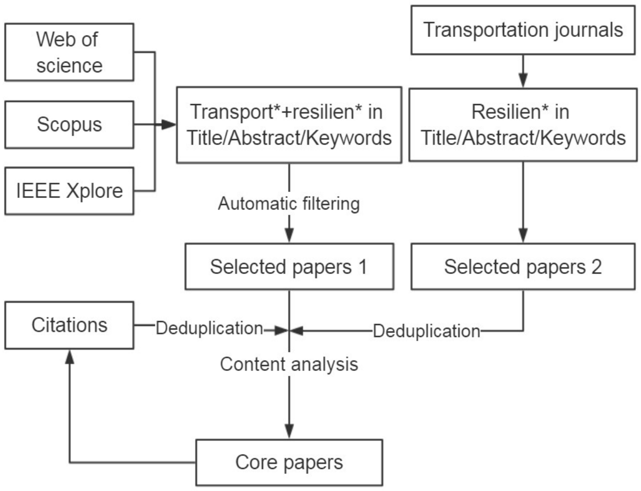


Fig. 1. Procedure of literature search.

appropriate keywords, we conduct both database search and journal-based search. The procedure of literature search is illustrated in Fig 1.

The databases selected are Web of Science, Scopus, and IEEE Explore. We search for "resilien*" and "transport*" in title, abstract, and keywords. We restrict the scope to academic papers in English, including journal papers and conference proceedings from 1990 to 2018.

All the papers obtained from three databases are combined, and after deleting the reduplicative papers, overall 1862 papers are selected. After going through those papers, we find that a large quantity of irrelevant papers lies in the discipline of (1) optical engineering or computer science, where "transport" is used as "transmission", and (2) structural/material engineering, where "resilient" means "elastic". Therefore, we use the following keywords to exclude irrelative papers: optical, wireless, multimedia, video, telecommunication, material, soil, and asphalt. After this step, we further do selection by hand based on abstract review. Finally, after deleting those papers which only note resilience in the title/abstract/keywords and provide no concrete discussions in main body, 76 papers are picked out.

Since we use keyword "transport*" in the database search, there may be some papers missed, in which the name of particular transportation mode is used, such as "road network", "railway", or "metro". Therefore, we conduct a supplement journal-based literature search. In this part, we restrict the search scope into the academic journals in the discipline of transportation. The list of journals is derived from JCR category: Transportation and Transportation Science & Technology. The selection rules are the same with those in database search except that only "resilien*" is set as the keyword. To exclude the papers that already appeared in the database search results, one more rule is added, that is, "NOT transport*". After abstract review, 20 more papers are added. Therefore, overall 96 papers are selected based on database search and journal-based search.

When we investigate these 96 articles in detail, some important citations being missed in aforementioned search are added. Eventually, there are overall 101 papers in the core set. It is noted that articles on interdependent transportation systems and other systems such as power grid or water supply systems are not included in this review. Note that articles focusing on the resilience of supply chain networks are excluded; a detailed review on this topic was provided in [9].

There are in total seven review papers related to this work. Hosseini et al. [8] presented a review on resilience in Engineering based on recently published papers. Mattsson and Jenelius [10] and Reggiani et al. [11] put the emphasis on the relation between vulnerability and resilience. Faturechi and Miller-Hooks [1] classified and analyzed frequently used performance metrics for transportation in disasters including resilience. References [12-14] also provided some discussions on resilient transportation. Compared with these review papers, our major contribution in this work is to try to cover the up-to-date papers specified on "resilience in transportation" and based on that to discuss the methods and strategies applied to measure and enhance resilience.

### B. Analysis

The number of selected publications each year is displayed in Fig. 2. We can see a distinct ascending trend, which implies that research on resilience of transportation system is becoming increasingly popular. According to our results, the first paper on resilient transportation was published in 2006.

Most of these papers were published on two categories of journals. One category is transportation related journals, among which Transportation Research Record is the most significant source, followed by Transportation research part A. Several mathematical modeling works were published on Computers & Operations Research. The other category is safety science related journals, including Reliability Engineering & System Safety, Safety Science, and Risk Analysis. There are 11 journals which contribute more than two papers in the core set, as listed in Table I.

The selected core articles are categorized according to transportation modes, including road network [15-53], freight transportation network [54-64], railway and metro network [2, 39, 65-73], general transportation network [74-81], waterway/maritime network [82-88], air network [89-95], and multimodal transportation networks [96-100] (Table II). The frequencies of different transportation modes are calculated to show the popularity.

We can see from Table II that the road network is the mostly studied transportation mode, which occupies nearly 50% of all the selected articles. The road network is the most important transportation mode in our daily life. Meanwhile, in emergency situations, road networks play a key role in conducting evacuation and relief resource distribution. The second most investigated transportation mode is the freight transportation network, which is the basis of domestic and international trade. Railway and metro are combined due to similar characteristics.

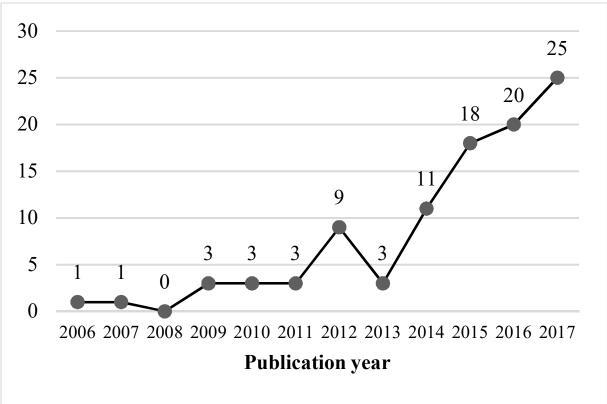

Fig. 2. Number of publications per year from 2006-2017

TABLE I
NUMBER OF ARTICLES PUBLISHED PER JOURNAL

| Journal title | #Articles |
|---|---|
| Transportation Research Record | 15 |
| Transportation Research Part A | 7 |
| Transportmetrica A | 6 |
| Transportation Research Part E | 5 |
| IEEE Transactions on Intelligent Transportation Systems | 4 |
| Transportation Research Part B | 4 |
| Risk Analysis | 4 |
| Journal of Infrastructure Systems | 4 |
| Transport Policy | 3 |
| Computers & Operations Research | 3 |
| Networks & Spatial Economics | 3 |

We find that few papers provide methods for general transportation networks. The reason is that different modes of transportation networks have different characteristics, and the methods used may be varied. The resilience of waterway networks and air transport networks is less significant as the infrastructure of these two types of networks has lower possibility of being damaged by disasters. The resilience of multi-modal transportation is significant while it has not drawn enough attraction; a discussion on this issue will be provided in the later section.

TABLE II
DIFFERENT TRANSPORTATION MODES STUDIED IN THE SELECTED CORE ARTICLES

| Transportation Mode (frequency) | References |
|---|---|
| Road network (44%) | Murray-Tuite (2006) [15], Berche et al. (2009) [16], Liu et al. (2009) [17], Bocchini and Frangopol (2010) [18], Wang et al. (2010) [19], Adams et al. (2012) [20], Bocchini and Frangopol (2012)[21], Chang et al. (2012)[22], Beiler et al. (2013)[23], Wang et al. (2013)[24], Faturechi et al. (2014)[25], Faturechi and Miller-Hooks (2014)[26], Osei-Asamoah and Lownes 2014[27], Bhavathrathan and Patil (2015)[28], Bhavathrathan and Patil (2015)[29], Freiria et al. (2015)[30], Testa et al. (2015)[31], Wang et al. (2015)[32], Ye and Ukkusuri (2015)[33], Alipour and Shafei (2016)[34], Shilling et al. (2016)[35], Soltani-Sobh et al. (2016)[36], Wang et al. (2016)[37], Zhang and Wang (2016)[38], Zhu et al. (2016)[39], Asadabadi and Miller-Hooks (2017)[40], Bagloee et al. (2017)[41], Donovan and Work (2017)[42], Kaviani et al. (2017)[43], Kim and Yeo (2017)[44], Mojtahedi et al. (2017)[45], Nogal et al. (2017)[46], Sadler et al. (2017)[47], Zhang et al. (2017)[48], Zhou et al. (2017)[49], Zhu et al. (2017)[50], Aydin et al. (2018)[51], Calvert and Snelder (2018)[52], Zhou and Wang (2018)[53], Liao et al. (2018)[101], Mudigonda et al. (2018)[102], Twumasi-Boakye and Sobanjo (2018)[103]. |
| Freight transportation network (13%) | Ta et al. (2009) [54], Nair et al. (2010) [55], Chen and Miller-Hooks (2012)[56], Miller-Hooks et al. (2012)[57], Abadi and Ioannou (2014)[58], Zhang and Miller-Hooks (2015)[59], John et al. (2016)[60], Chen et al. (2017)[61], Darayi et al. (2017)[62], Fotuhi and Huynh (2017)[63], Asadabadi and Miller-Hooks (2018)[64]. |
| Railway and metro (12%) | Cox et al. (2011)[65], Bruyelle et al. (2014)[66], Collis et al. (2014)[67], D'lima and Medda (2015)[68], Adjetey-Bahun et al. (2016)[69], Azad et al. (2016)[70], Chan and Schofer (2016)[71], Chopra et al. (2016)[2], Zhu et al. (2016)[39], Armstrong et al. (2017)[72], Whitman et al. (2017)[73], Bababeik et al. (2018)[104], Janić (1018)[105]. |
| General transportation network (9%) | Ip and Wang (2011)[74], Serulle et al. (2011)[75], Freckleton et al. (2012)[76], Tamvakis and Xenidis (20120[77], Reggiani (2013)[78], Hartmann (2014)[79], Vugrin et al. (2014)[80], Zhang et al. (2015)[81]. |
| Waterway/Maritime network (8%) | Campo et al. (2012)[82], Omer et al. (2012)[83], Baroud et al. (2014)[84], Baroud et al. (2014)[85], Baroud et al. (2015)[86], Farhadi et al. (2016)[87], Hosseini and Barker (2016)[88]. |
| Air network (8%) | Janić (2015)[89], Stroeve et al. (2015)[90], Belkoura et al. (2016)[91], Dunn and Wilkinson (2016)[92], Filippone et al. (2016)[93], Yoo and Yeo (2016)[94], Voltes_dorta et al. (2017)[95], Clark et al. (2018)[106]. |
| Multimodal transportation network (6%) | Schintler et al. (2007)[96], JIn et al. (2014)[97], Stamos et al. (2015)[98], Marzuoli et al. (2016)[99], Hua and Ong (2017)[100]. |

## III. DEFINITION OF RESILIENCE IN TRANSPORTATION

Although the origin and definition of resilience in transportation systems have been discussed in some review papers, they merely covered part of the papers that we finalize.

In this section, we review the definitions given in all the papers obtained by our literature search. Furthermore, to clarify the connotation of resilience in the context of transportation systems, the connection and difference between resilience and several related concepts, specifically risk, reliability, vulnerability, and robustness, are discussed.

### A. *Definition in the Literature*

Based on the literature search results, Murray-Tuite [15] is the first to specifically define resilience in the context of transportation systems, not general infrastructure systems, and propose measures of resilience. In that work, resilience is considered to have ten dimensions, including redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly. These ten dimensions are so complex and interacted that it is difficult to obtain a comprehensive measure. The author provided multiple metrics for the last four dimensions. Murray-Tuite also compared the impact of system optimum and user equilibrium on the resilience of transportation systems with respect to these four dimensions. Since then, the concept of resilience has been utilized in various transportation modes.

The definitions of resilience proposed in some featured studies are listed in Table III. The definitions of resilience in different transportation modes are mostly based on the same general idea, with some modifications according to the characteristics of specific transportation modes.

All these definitions quantify the resilience of transportation systems from one or both of the following two perspectives: (1) the ability to maintain functionality under disruptions, and (2) time and resources required to restore performance level after disruptions. As shown in Fig. 3, the first perspective relates to the disruption phase, ranging from the happening of disruption to the time point when the system performance reaches the minimum value; the second perspective relates to the recovery phase, ranging from the beginning of recovery to the point when the systematic performance returns to a stable state. This figure is adapted from the one proposed by Bruneau et al. [103] which studied seismic resilience of communities. One important change is that, in the original graph, there is no disruption phase, and the system performance drops to the minimum value immediately at time $t_0$, which is reasonable for the earthquake scenario. While in transportation systems, disruptions may last for some time, such as the damage caused by hurricanes. There is another variety in the literature [107], which allows the inequality between $P(t_0)$ and $P(t_2)$, i.e. it is unnecessary for the system to recover to the original level of performance at the pre-disruption state.

TABLE III
DEFINITIONS OF RESILIENCE IN DIFFERENT MODE OF TRANSPORTATION SYSTEMS IN SOME FEATURED WORKS

| Reference | Transportation mode | Definition |
|---|---|---|
| Murray-Tuite (2006) [15] | Road network | Characteristic indicating (1) system performance under abnormal conditions, and (2) the speed and resources required for recovery to original functional states.<br>Ten dimensions: redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly. |
| Beiler et al. (2013)[23] | Road network | Four properties: robustness, redundancy, resourcefulness, and rapidity. |
| Bhavathrathan and Patil (2015)[29] | Road network | "A measure of maximum agitation a system can take in before getting displaced from one state to another." |
| Serulle et al. (2011)[75] | General transportation network | The ability of the transportation system to (1) absorb disruptive events gracefully and (2) restore its pre-disruption level of service in a specified time frame. |
| Henry and Emmanuel (2012)[101] | General transportation network | A time-dependent ratio of recovery to loss suffered by the system at some previous point. |
| Bocchini et al. (2014)[102] | General transportation network | Four dimensions: technical, organizational, social, and economic.<br>Four properties: robustness, rapidity, redundancy, and resourcefulness.<br>Three results: more reliability, faster recovery, and low consequences. |
| Ta et al. (2009)[54] | Freight transportation network | "The ability for the system to absorb the consequences of disruptions to reduce the impacts of disruptions and maintain freight mobility." |
| Nair et al. (2010)[55], Chen and Miller-Hooks (2012)[56] | Freight transportation network | "The post-disaster expected fraction of demand that, for a given network configuration, can be satisfied within specified recovery costs (budgetary, temporal, and physical)." |
| Chen et al. (2017)[61] | port-hinterland container transportation network | "The ability of the system, with the help of immediate recovery activities, to meet the transport demand, as well as to recover and ensure the persistence of the performance level at a rational cost within a limited period, when faced with disruptions to the network caused by unconventional emergency events." |
| Mansouri et al. (2009)[83] | Maritime transportation system | "A function of system's vulnerability against potential disruption, and its adaptive capacity in recovering to an acceptable level of service within a reasonable timeframe after being affected." |
| Baroud et al. (2014, 2015)[84,85] | Inland waterway networks | "A time-dependent proportional measure of how the system is performing relative to an as-planned performance level."<br>Four dimensions: reliability, vulnerability, survivability, and recoverability. |
| Janić (2015)[89] | Air transport network | "The ability to withstand and stay operational at the required level of safety during the impact of a given disruptive event."<br>Three layers: physical, service, and cognitive. |
| Chan and Schofer (2016)[71] | Rail transit system | "The ability to experience a negative, potentially damaging event and return to a healthy state of operations in a reasonable amount of time after that event." |
| D'Lima and Medda (2015)[68] | Metro | "The speed with which a system recovers from disruptive events or shocks." |

Bruneau et al. [103] firstly proposed that resilience consists of four properties: robustness, redundancy, resourcefulness, and rapidity. This "R4 framework", named by Tierney and Bruneau [110], was then considerably employed in subsequent studies on resilience. In our understanding (Fig. 3), the level of robustness and redundancy determine the performance (loss) of the transportation system in disruption phase. Specifically, robustness measures the ability to withstand disaster-induced damage and redundancy reflects the availability of alternative resources. Resourcefulness and rapidity together determine the ability to restore functionality in recovery phase. In transportation systems, resourcefulness represents the amount of available repair units in post-disaster operations, and rapidity assesses the ability to make the best of these resources and restore the pre-disruption level of service rapidly.

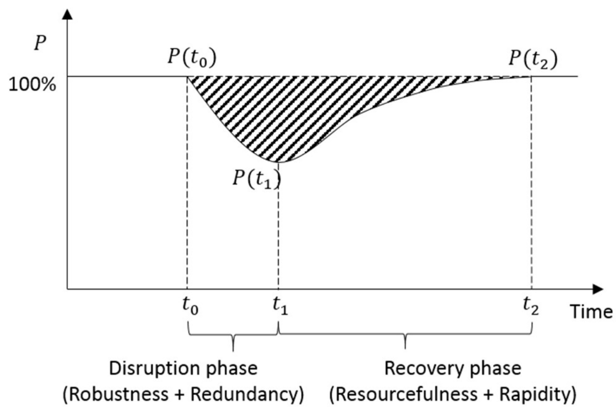


Fig. 3. Two phases of resilience measurement (Adapted from [103])

### B. Related Concepts

As summarized in Faturechi and Miller-Hooks [1], the concepts utilized in the literature to evaluate the performance of transportation systems in disasters include resilience, robustness, reliability, risk, vulnerability, survivability and flexibility. As the last two concepts are seldom used compared with other five, this section mainly discusses the relationships among resilience, robustness, reliability, risk, and vulnerability.

We first divide these five concepts into two groups: (1) group 1 with resilience, robustness, and reliability that assess the system's remaining performance from a positive perspective, and (2) group 2 with risk and vulnerability that measure the damage to the system from a negative perspective.

Accurately, risk is not a systematic performance indicator, but a concept used to quantify the threat of an event. Risk is usually expressed as the probability of occurrence of an event multiplied by the corresponding consequence. Vulnerability captures the susceptibility of transportation systems to incidents or disasters.

Next, we discuss the differences among resilience, robustness, and reliability. Among these three, reliability is more different from the rest two, as reliability describes the ability of a system to perform as designed under stated conditions without involving perturbations/disruptions. Differently, robustness measures the ability of a system to maintain its initial state when facing perturbations. In practice, robustness is measured by the remaining level of functionality under disruptions, while reliability is measured by the probability of meeting a required level of service.

Both robustness and resilience measure the system's performance in the context of disruptions. The key difference is that a robust transportation system can resist the impact of disruptions and maintain its original state. However, if the disruptions are too huge for the system to maintain its original state, we are talking about resilience. After the system shifts to an imbalanced situation, resilience measures the ability of the system to rebalance its demand and supply. The rebalanced level of functionality and the time and resources required can be used to measure resilience.

## IV. Measurement of Resilience

In this section, we review the methods proposed in the literature to measure resilience of transportation systems. Generally, there are two steps to measure resilience. The first step is to give a metric for measurement, and the second step is to calculate the metric with some evaluation approaches. Next, we will review the metrics and measurement approaches, respectively.

### A. Resilience Metrics for Transportation System

The metrics are divided into three categories: topological metrics, attributes-based metrics, and performance-based metrics. Topological metrics are usually constructed on some topological properties, such as betweenness centrality, or shortest path length. Attributes-based metrics and performance-based metrics consider both structures of transportation systems and the traffic flow on them. The difference between attributes-based and performance-based metrics is that the former only evaluate resilience from some specific aspects of resilience, such as recovery speed, while the latter are designed to assess systems' resilience in a comprehensive way.

#### 1) Topological Metrics

Topological metrics focus on the structure of the transportation systems while ignoring the dynamic features. They are usually constructed on some graph-based properties, such as betweenness centrality, or shortest path length. The topological metrics used in the literature to evaluate resilience are listed in Table IV. Although these metrics are defined in different ways, most of them compare the structure of the transportation network with corresponding complete graph. The two most used metrics are the size of giant component and average shortest paths. The size of giant component assesses the proportion of nodes connected in disruptions. It measures the ability of the network to keep connected in emergency situations. Average shortest paths reflect the connection strength of a network. Another metric efficiency, as shown in Table IV, is the average of the inverse of shortest paths.

All the metrics in Table IV are borrowed from existing studies, while there are also some papers which proposed novel topological metrics for resilience measurement. Ip and Wang [74] proposed a resilience metric based on reliable passageways. Network resilience is defined as the weighted sum of the

TABLE IV
TOPOLOGICAL METRICS FOR TRANSPORTATION RESILIENCE

| Reference | Metrics |
|---|---|
| Schintler et al.[96] | Network diameter<br>Average shortest paths |
| Berche et al.[16] | Size of giant component<br>Average shortest paths |
| Osei-Asamoah and Lownes[27] | Efficiency: $\frac{1}{N(N-1)}\sum_{i\neq j}\frac{1}{d_{ij}}$<br>Size of giant component |
| Hartmann[79] | Backup capacity: $c_b = \max_{\{i,j\}}(\tilde{l}_{i,j} - l_{i,j})$ |
| Testa et al.[31] | Average node degree<br>Clustering coefficient: $\frac{\lvert E(\Gamma_i)\rvert}{\frac{1}{2}d(i)(d(i)-1)}$<br>Betweenness centrality<br>Redundancy: $\frac{1}{(\lvert s\rvert-1)^2}\sum_{j\in V(\Gamma_i^2)} I(i,j)$ |
| Chopra[2] | Degree assortativity coefficient:<br>$\frac{l^{-1}\sum_{(i,j)\in L} k_i k_j - \left[l^{-1}\sum_{(i,j)\in L}\frac{k_i+k_j}{2}\right]^2}{l^{-1}\sum_{(i,j)\in L}\frac{k_i^2+k_j^2}{2} - \left[l^{-1}\sum_{(i,j)\in L}\frac{k_i+k_j}{2}\right]^2}$ |
| Aydin et al.[51] | Betweenness centrality<br>Size of giant component<br>Efficiency |
| Zhang and Miller-hooks [81] | Average degree<br>Network diameter<br>Cyclicity |

Note: $d_{ij}$ is the shortest path length of node $i$ and $j$. $\tilde{l}_{i,j} - l_{i,j}$ is the increase of edge-betweenness after the removal of the edge with largest edge-betweenness. $|E(\Gamma_v)|$ is the number of links in the neighborhood of node $v$. $d(v)$ is the number of nodes in the neighborhood of node $v$. $I(i,j)$ is the number of node-independent paths between node $i$ and $j$. $\Gamma_i^2$ is the neighborhood of the vertices in the neighborhood of $i$. $|s|$ is the number of independent paths between $i$ and the complete graph. $l$ represents the number of links in $L$, and $k$ is node degree.

resilience of all nodes, while node resilience is evaluated by the weighted average number of reliable passageways, as shown in Equation (1). Parameter $P_k(i,j)$ is the reliability of a passageway, while $\omega_i$ and $v_j$ are separately the population weight and self-exhausted weight of the node. With amount of test examples, the authors claimed that the most resilient network should have almost even node degrees. Zhang and Wang extended this concept, and proposed a resilience-based performance metric to study risk mitigation [38] and post-disaster recovery [48] of bridge network. Similarly, Janić [89] proposed a resilience metric for air transport network (Equation (2)). $w_i^{\gamma_i}(\tau)$ is the airport relative importance calculated by dividing the number of flights accommodated at airport $i$ by that at all the airports. $R_i^{\gamma_i}(\tau)$ is the airport resilience defined as the sum of the product of self-excluding importance and the number of arriving or departing flights.

$$R(G) = \sum_{i=1}^{n} \omega_i \sum_{j=1, j\neq i}^{n} v_j \sum_{\forall k\ link(i,j)} P_k(i,j) \tag{1}$$

$$R^{\gamma}(N,\tau) = \sum_{i=1}^{N} w_i^{\gamma_i}(\tau)\, R_i^{\gamma_i}(\tau) \tag{2}$$

### 2) *Attributes-based Metrics*

As discussed in section III, resilience is considered to have four properties, i.e. robustness, redundancy, resourcefulness, and rapidity [103]. As shown in Fig. 3, each of these properties corresponds to a period of resilience measurement. Attributes-based metrics usually focus on one or several of these properties and try to measure the resilience of transportation system based on the performance at specific periods. The attributes-based metrics used in the literature to assess resilience are listed in Table V.

TABLE V
ATTRIBUTES-BASED METRICS FOR TRANSPORTATION RESILIENCE

| Reference | Metrics |
|---|---|
| Murray-Tuite[15] | Adaptability: atypical uses of systems<br>Safety: number of traffic incidents<br>Mobility: network-wide efficiency<br>Recovery: time required to alleviate congestion |
| Adams et al.[20] | Reduction: $\frac{P(t_1)-P(t_0)}{t_1-t_0}$ *<br>Recovery: $\frac{P(t_2)-P(t_1)}{t_2-t_1}$ * |
| Beiler et al.[23] | Travel time index: travel time in peak period over that under normal conditions<br>Redundancy: availability of alternate routes |
| D'Lima et al.[68] | Speed of returning to equilibrium |
| Wang et al.[32] | Rapidity: speed to returning to normal state |
| Hosseini et al. [88] | Absorptive, adaptive, and restorative capacities |
| Soltani-Sobh et al.[36] | Operational cost<br>Expected failure cost |
| Yoo and Yeo[94] | Adaptive capacity: the ability of a network that an attacked node can be replaced by adjacent nodes |
| Hua and Ong[100] | Total unaffected passenger flow |
| Mojtahedi et al.[45] | Recovery rate |

Note: * as defined in Fig. 3.

As we can see from Table V, over half of the articles focus on the recovery phase to assess resilience. Specifically, two main metrics are recovery speed, which indicates the time required for the system to return to an equilibrium state, and recovery efficiency, which represents the resources required for recovery. Even though robustness and redundancy are important properties of resilience, the ability to recover after deviating from equilibrium state is the main connotation that resilience outweighs the other concepts as a more comprehensive metric for assessing the performance of transportation systems in disasters.

### 3) *Performance-based Metrics*

Different from attributes-based metrics, performance-based metrics are designed to measure systems' resilience based on their performance over the whole period affected by disasters. Three most widely used performance-based metrics are identified in the literature: (1) degradation of system quality over time, firstly proposed by Bruneau [103] , (2) time-dependent ratio of recovery to loss, firstly proposed by Henry and Emmanuel [101], and (3) expected fraction of demand satisfied in post-disaster network using specific recovery costs, firstly proposed by Chen and Miller-Hooks [56]. In this section, these three metrics and their extensions will be introduced respectively, followed by some other metrics.

Bruneau et al. [103] pointed out that system resilience should be measured according to the ability to (1) reduce failure probabilities, (2) reduce failure consequences, and (3) reduce recovery time, when studying seismic resilience. Based on this idea, they proposed a resilience metric as in Equation (3), where $Q(t)$ is the quality of the system, $t_0$ is the occurrence time of disruption and $t_0+\tau$ is the completed time point of recovery. We can easily find that the value of this indicator is equal to the shaded area in Fig. 3. In other words, resilience is measured by all the performance loss from the occurrence of disaster to the full recovery of system performance.

$$R=\int_{t_0}^{t_0+\tau}[100-Q(t)]dt \tag{3}$$

This metric was then employed by Bocchini and Frangopol [18, 21] to measure the resilience of road networks when optimizing the restoration sequence of damaged bridges. The quality of the system $Q(t)$ is quantified by a performance metric based on total travel time and total travel distance. Adjetey-Bahun et al. [69] used this metric to quantify the resilience of railway systems. Passenger load and passenger delay are used to measure the quality of the system. This metric was also applied to road and subway systems affected by hurricans [39, 50]. The quality of the system is measured by the percentage of evacuees leaving the risk area by time. Additionally, Bocchini and Frangopol [21] and Adjetey-Bahun et al. [69] made some modifications to the metric, as shown in Equation (4). The total performance loss is divided by the time horizon. In these two works, resilience is measured by the average performance loss over the investigated time horizon.

$$R=\int_{t_0}^{t_0+\tau}\frac{[100-Q(t)]}{\tau}dt \tag{4}$$

The second performance-based resilience metric was developed by Henry and Emmanuel [101]. They defined five system states in the life-cycle of disasters: stable original state, system disruption, disrupted state, system recovery, and stable recovered state. A time-dependent resilience metric is defined as the ratio of recovery at time t to function loss at some previous time point. The resilience of the system at time $t_r$ under disrupted event $e_j$ can be calculated by Equation (5). Parameter $F(t_r|e_j)$ is the function of system at time $t_r$ resulting from disruption $e_j$, $F(t_d|e_j)$ is the minimum function, and $F(t_0)$ is the function of the system at pre-disruption state. This indicator treats resilience as a dynamic property of systems and is more consistent with the original definition of resilience, i.e. the ability to bounce back. Supposing that the function of the system can restore to its pre-disruption level, then the system is fully resilient. This metric was then used to study the resilience of inland waterway network [84-86], and marine transportation systems [87].

$$R_F(t_r|e_j)=\frac{F(t_r|e_j)-F(t_d|e_j)}{F(t_0)-F(t_d|e_j)} \tag{5}$$

The third widely used performance-based resilience metric was proposed in [56] when studying the resilience of freight transportation systems. Resilience is defined in Equation (6) as the expected fraction of demand satisfied by the post-disaster network using specific recovery costs. Parameter $d_\omega$ represents the maximum demand satisfied for origin-destination pair $\omega$ by the post-disaster network, and $D_\omega$ represents the demand satisfied for origin-destination pair $\omega$ by the pre-disaster network. The expectation value is used here as arc capacities are considered to be stochastic. This metric was then employed to study the resilience of intermodal freight systems [55], freight transportation networks [57], airport pavement networks [25], roadway networks [26], metro networks [97], air transport networks [89], and port-hinterland container transportation network [61]. Zhang et al. [81] used this indicator to investigate the impact of network topology on transportation network resilience. Janić [89] combined this metric with the measurement proposed in [74]. It is noted that Janić calculated the airport weights by flights accommodated, rather than using topological characteristics as in [74].

$$R=E\left(\sum_{\omega\in W}d_\omega\Big/\sum_{\omega\in W}D_\omega\right)=\frac{1}{\sum_{\omega\in W}D_\omega}E\left(\sum_{\omega\in W}d_\omega\right) \tag{6}$$

In addition to the above mentioned three widely used resilience metrics, there are several more as described below.

Cox et al. [65] introduced the definition of economic resilience proposed in [111] to transportation, and developed a resilience indicator in Equation (7). Parameter $\%\Delta DY^m$ represents the maximum percentage change in system performance resulting from disasters, and $\%\Delta DY$ is the expected percentage change in system performance resulting from disasters.

$$R=\frac{\%\Delta DY^m-\%\Delta DY}{\%\Delta DY^m} \tag{7}$$

By using system travel time as the indicator of performance, Omer et al. [83] (Equation 8), Faturechi and Miller-Hooks [26] (Equation 9), and Bhavathrathan and Patil [29] (Equation 10) developed three similar resilience metrics. In Equation (8), $t_{ij(before\ shock)}$ and $t_{ij(after\ shock)}$ are respectively the travel time between node $i$ and node $j$ before and after shock. The underlying idea of this metric is the same as Equation (3). In Equation (9), $tt^0$ is the total travel time at pre-event state, while $tt^r$ is the total travel time at pre-action state. In Equation (10), $ESTT$ refers to expected system travel time. Parameter $ESTT_0$ represents the minimum possible $ESTT$ at pre-disruption state, and $ESTT_{Cr}$ represents the maximum $ESTT$ with demand satisfied. This indicator aims to capture the maximum agitation that the transportation system can undertake.

$$R=\frac{\int_0^t \frac{t_{ij(before\ shock)}}{t_{ij(after\ shock)}}dt}{t} \tag{8}$$

$$R=\frac{{tt^r}^{-1}}{{tt^0}^{-1}} \tag{9}$$

$$R=1-\frac{ESTT_0}{ESTT_{Cr}} \tag{10}$$

One important difference between the indicators in Equation (8) and (9-10) is that the one in Equation (8) accounts for the changing trend of resilience, while the other two only consider the performance at the end time.

Chan and Schofer [71] used lost service days (LSD) to measure the resilience of rail transit, as shown in Equation (11). $RVM_n$ denotes revenue vehicles miles per day under normal condition, and $RVM_d$ denotes revenue vehicle miles per day at disrupted state. This metric can be generalized to study the resilience of public transportation systems facing extreme weather events.

$$LSD = \sum_{t=sta}^{t=end} \frac{RVM_n - RVM_d}{RVM_n} \quad (11)$$

In addition to time costs, Vugrin et al. [80] considered the amount of resource expenditures required for recovery. The metric is shown in Equation (12-14), where $SI$ is the cumulative impact of disruption on system performance, $TRE$ is the total recovery effort, and $\alpha$ is a weighting factor. In Equation (13), $x_i(t)$ is the flow on link $i$ at time $t$ under disruption, $H_i[x_i(t)]$ is the cost on link $i$, $H_i^0(t)$ is the cost on link $i$ at pre-disruption state, $e_{rs}(t)$ is the volume of traffic demand that cannot be satisfied between origin-destination pair $rs$, and $\gamma_{rs}$ is penalty costs. In Equation (14), $C_{ijm}$ is the cost for conducting repair task $j$ on link $i$ in mode $m$, and $u_{ijmt}$ is a binary variable which indicates whether the corresponding task is conducted. This metric integrates: (1) the ability to maintain functional under disruption, and (2) time and resources required to restore performance level after disruption.

$$R = SI + \alpha TRE \quad (12)$$

$$SI = \sum_{t=1}^{T} \left[ \sum_i \{H_i[x_i(t)] - H_i^0(t)\} + \sum_{rs} \gamma_{rs} e_{rs}(t) \right] \quad (13)$$

$$TRE = \sum_i \sum_j \sum_m \sum_t C_{ijm} u_{ijmt} \quad (14)$$

In general, we think that performance-based metrics are more appropriate than attributes-based metrics to measure the resilience of transportation systems, and both of them are better than topological metrics as the latter do not consider the flows in the network. Among all these performance-based metrics, those in equation (4), (5), (8), and (12) are better as they account for the performance of the system during the whole process not just that at some specific time points. It is also noted that the metric in (12-14) involves resource expenditures required for recovery into the assessment of resilience, while the others usually consider recovery resources as constraints in their models.

### *B. Measurement Approaches*

Measurement approaches are used to provide the performance assessment of transportation systems for the calculation of resilience metrics. These performance evaluation approaches can be categorized as optimization models, topological models, simulation models, probability theory models, fuzzy logic models, and data-driven models.

TABLE VI
LITERATURE REVIEW FOR THE OPTIMIZATION MODELS

| Reference | Decision variables | Objective | Constraints |
|---|---|---|---|
| Liu et al.[17] | Bridges to be retrofitted | Min repair cost and flow cost | Flow conservation, link capacity, and budget |
| Bocchini and Frangopol[18] | Starting time of restoration and restoration pace of bridges | Max resilience and min cost of intervention | Time limit, restoration pace range, and budget |
| Nair et al.[55] | Recovery activities to be undertaken | Max expected throughput | Flow conservation, link capacity, level of service, and budget |
| Bocchini and Frangopol[21] | Starting time of restoration and restoration pace of bridges | Max resilience, min recovery time, and min restoration cost | Time limit, restoration pace range, target level of functionality, and budget |
| Chang et al.[22] | Bridge retrofit prioritization | Max network evacuation capacity and min total retrofit cost | Flow conservation, link capacity, and budget |
| Chen and Miller-Hooks[56] | Recovery activities to be undertaken | Min unsatisfied demand | Flow conservation, link capacity, level of service, and budget |
| Miller-Hooks et al.[57] | Preparedness and recovery activities to be undertaken | Max network throughput | Flow conservation, link capacity, level of service, and budget |
| Abadi and Ioannou[58] | Usage of unusual resources and routes | Min total cost | Link capacity and demand satisfaction |
| Faturechi et al.[25] | Preparedness activity and repair action | Max satisfied demand | Space for equipment storage, flow conservation, network capacity, repair time, and budget |
| Faturechi and Miller-Hooks[26] | Preparedness and response activity | Max travel time resilience | Flow conservation, link capacity, implementation time of response action, and budget |
| Jin et al.[97] | Selection of localized integration plan | Max satisfied travel demand | Flow conservation, link capacity, node capacity, intermodal transfer, budget |
| Zhang and Miller-Hooks[59] | Order of recovery activities | Max network throughput | Flow conservation, link capacity, budget, and recovery time limit |
| Azad et al.[70] | Recovery plan | Min total cost | Link capacity, node capacity, demand requirement, and transportation time |
| Marzuoli et al.[99] | Assignment of passengers to rerouting options | Min cost of re-accommodation of diverted passengers | Flight capacity, motor-coach capacity, time limit, and passenger conservation |
| Soltani-sobh et al.[36] | Location of recovery center | Min operational cost and expected failure cost | Center coverage |
| Zhang and Wang[38] | Selection of constructing or retrofitting bridges | Max network performance and min total cost | Candidate bridges |
| Asadabadi and Miller-Hooks[40] | Height improvement and rebuilt of link sections, and improvement of drainage system | Min investment cost and expected future cost | Flow conservation, link capacity, demand requirement, and budget |
| Chen et al.[61] | Recovery activities to be undertaken | Min handling time, recovery cost, and economic loss | Port capacity and time limit |
| Kaviani et al.[43] | Location of roadside guidance devices | Min total travel time | Resource limitation, flow conservation, and link capacity |

### 1) Optimization Models

Optimization modes are mostly used to address two issues: (1) solving traffic assignment problem, such as user equilibrium (UE), or system optimal (SO), and (2) optimizing the utility of mitigation/preparedness/response/recovery resources. The optimization models proposed in the literature are shown in Table VI. The decision variables, objective functions, and constraints are summarized.

### 2) Topological Models

Topological models correspond to the topological metrics as listed in Table IV. Different from optimization models, topological methods usually have explicit expressions. Some of them rely on the calculation of shortest path [16, 27, 51, 74, 79], and some of them are determined by node degree distribution [2]. A widely used metric, size of giant component, is calculated by identifying the proportion of nodes keeping connected as one cluster [16, 92, 94]. In the literature, size of giant component and efficiency are repeatedly calculated in different disruption scenarios to assess the property of the network. However, Zhou and Wang [112] recently proposed a method for analytically calculating network efficiency with different disruptions.

### 3) Simulation Models

Based on our literature review, simulation methods are rarely used in the assessment of transportation resilience. As discussed above, some papers conducted failure simulations on transportation systems to examine the change of topological metrics. Simulations in these papers are not used to directly assess performances, but to give some input settings.

Murray-Tuite [15] used DYNASMART-P to generate UE and SO assignment for a test network and further assessed the adaptability, safety, mobility, and recovery of this network. Adjetey-Bahun et al. [27] proposed a simulation-based model to quantify the resilience of mass railway transportation system. The performance indicators they chose are passenger delay and passenger load. The input data includes the number of passengers entering each station during each hour, and train timetable, while the outputs are the two indicators. Passengers are assumed to take the shortest paths to their destination. The outputs under normal situation and that with perturbations are compared to examine the resilience of the system.

Kim and Yeo [44] used macroscopic fundamental diagram (MFD) to evaluate link criticality. In order to compare the MFD in normal condition with that in event condition, they conducted simulation on a real-world network with randomly generated demand and assumed link disruption.

### 4) Probability Theory Models

Baroud et al. [84] used a stochastic extension of the metric proposed in Equation (5). A stochastic parameter $V_i^j$ is defined to describe the performance reduction of component $i$ due to event $e_j$. Then, the corresponding recovery time $U_i^j$ is viewed as the function of $V_i^j$. Finally, the summation of recovery time $U_i^j$ is used to determine the probability that total system restoration is completed before mission time.

Hosseini and Barker [88] developed a Bayesian network model to quantify the resilience of inland waterway ports as a function of absorptive, adaptive, and restorative capacities. John et al. [60] also used Bayesian belief networks to model and rank the influencing variables in a seaport system. Bayesian networks are widely used in reliability engineering. With efficient data sets, the casual relationships and sensitivity among different aspects of resilience are well studied.

### 5) Fuzzy Logic

Fuzzy logic is a multi-value logic which uses real number from 0 to 1 to represent the truth of variables. Fuzzy logic is a popular tool when there is no explicit mathematical models while all the relative attributes to one concept can be involved. Heaslip et al. [113] firstly utilized fuzzy logic to quantify resilience of transportation systems. Serulle et al. [75] extended this model by refining key variables, adjusting model interactions, and increasing transparency between metrics. Nine variables were selected, including road available capacity, road density, alternate infrastructure proximity, level of intermodality, average delay, average speed reduction, personal transport cost, commercial–industrial transport cost, and network management. Nine levels of truth from extremely low to extremely high were used. Freckleton et al. [76] further improved this method by introducing more input variables.

### 6) Data-driven Models

With the advancement of data acquisition and storage, data-driven methods have become popular in different areas. In this literature review, we find over ten papers which used real data to assess the resilience of transportation systems. Different from the above-mentioned methods, data-driven methods do not look into the inherent mechanism of the system, but directly choose some recorded data which can reflect the change of system performance in different scenarios to assess the system's property. Statistical methods are sometimes used to pre-process the data before used as performance indicators. The data that used in different works to indicate system's performance is summarized in Table VII.

TABLE VII
DATA USED AS PERFORMANCE INDICATORS

| Reference | Transportation mode | Data used |
|---|---|---|
| Cox et al.[65] | Metro | Number of passenger journeys |
| Adams et al.[20] | Freight network | Truck counts and truck speed variations |
| D'Lima and Medda[68] | Metro | Passenger counts |
| Stamos et al.[98] | Multiple modes | change of transportation modes |
| Belkoura et al.[91] | Air network | Planned and executed trajectories |
| Chan and Schofer[71] | Rail network | Revenue vehicle-miles |
| Farhadi et al.[87] | Marine transportation network | Vessel dwell time and net vessel transit counts |
| Zhu et al.[39, 50] | Metro and road network | taxi trips and subway ridership |
| Donovan and Work[42] | Road network | Travel distance and time of taxis |
| Loo and Leung[108] | Metro and Road network | MTR service frequency and road traffic flows |
| Mojtahedi et al.[45] | Road network | Reconstruction time and cost |

It is worth mentioning that some articles have used integrated methods, and can be categorized into more than one subsections. These papers listed in the above tables are given as exemplary, and may not be exhaustive.

## V. Enhancement of Resilience

TABLE VIII
Literature Review for Enhancement Strategies of Transportation Resilience

| Reference | Phase(s) | Strategies |
|---|---|---|
| Liu et al.[17] | Mitigation | Optimizing allocation of retrofit resources to highway bridges |
| Chang et al.[22] | Mitigation | Selecting bridges to be retrofitted and specific schemes for them |
| Zhang and Wang[38] | Mitigation | Optimizing bridge retrofitting and new construction |
| Fotuhi and Huynh[63] | Mitigation | Optimizing retrofitting of rail links, location of new terminals, and expansion of existing terminals |
| Asadabadi and Miller-Hooks[40] | Mitigation | Building seawalls, raising the height of roadways, and improve drainage systems |
| Soltani-Sobh et al.[36] | Preparedness | Optimizing pre-positioning of recovery centers for bridges restoration |
| Abadi and Ioannou[58] | Response | Reconfiguring to include normally ineffective resources and routes |
| Jin et al.[97] | Response | Integrating disrupted metro network with localized bus services |
| Dunn and Wilkinson[92] | Response | Redirecting air routes from disrupted airports to closest operational ones |
| Wang et al.[19, 24] | Response | Conducting contraflow and reconstruction of selected roads |
| Bocchini and Frangopol[18] | Recovery | Optimizing intervention schedule for highway bridges |
| Nair et al.[55] | Recovery | Optimizing recovery activities on links between terminal processes |
| Chen and Miller-Hooks[56] | Recovery | Optimizing recovery activities on modal or transfer arcs |
| Baroud et al.[85] | Recovery | Optimizing recovery schedule for water way links |
| Vugrin et al.[80] | Recovery | Optimizing recovery modes and sequences for disrupted links |
| Zhang and Miller-Hooks[59] | Recovery | Optimizing recovery schedule for rail links |
| Zhang et al.[48] | Recovery | Optimizing restoration schedule for road-bridge network links |
| Miller-Hooks et al.[57] | Preparedness and recovery | Optimizing preparedness activities and recovery activities on each link |
| Faturechi et al.[25] | Preparedness and response | Optimizing pre-prepared teams and equipment and repair actions on links |
| Faturechi and Miller-Hooks[26] | Mitigation, preparedness, and response | Optimizing link retrofit, capacity expansion, resources preparedness, and link response actions |

In the literature, enhancement of resilience is mostly accompanied by measurement of resilience, which is used to assess the effectiveness of enhancement strategies. As the mathematical models used to measure resilience are reviewed and well discussed in the last section, this section will focus on the specific strategies adopted in the literature to enhance resilience of transportation systems.

The life cycle of a disaster is usually divided into four phases: mitigation, preparedness, response, and recovery [1]. We find that all the strategies used to enhance the resilience of transportation systems target at one or several of these phases. As shown in Table VIII, the second column shows the phase(s) the strategy belongs to, and the third column presents the specific strategies used.

We can find that most papers target on only one phase and provide strategies. Mitigation strategies try to retrofit the transportation network, especially the vulnerable components, to improve its ability to resist disruptions. However, in some cases, disasters cannot be avoided, or the cost of retrofitting is too high, then preparedness of resources at pre-disaster stage will benefit post-disaster response or recovery. The difference between response strategies and recovery strategies is that the former usually provide some temporary actions to accommodate the demand, such as using bus service to support disrupted metro networks [97], or conducting contraflow to accelerate evacuation [19, 24]. These actions aim at alleviating the effects of disasters and avoiding cascading failures. Response actions will be cancelled later and replaced by recovery actions with the purpose of restoring the original state of the system.

## VI. Several Popular Subtopics

In the previous sections, we have reviewed the definitions of transportation resilience proposed in the literature, the metrics and mathematical models used to measure resilience, and strategies employed to enhance resilience. In addition, we also identified two popular subtopics in the literature: (1) enhancing transportation resilience by identifying and improving critical components, and (2) resilience of transportation systems in the context of climate change/extreme weather events.

### A. *Critical Component Analysis*

One key constraint to implement strategies to enhance resilience is the limitation of resources. In either pre-disaster mitigation and preparedness phases or post-disaster response and recovery phases, it is impossible to allocate resources to all the network components. Therefore, it is helpful to identify the critical components, whose improvement will benefit the system most, or whose degradation will suffer the system most.

The normal practice of identifying critical component is to remove this component from the network and then regard the increased cost as the importance of this component. Then the criticality of all the components can be ranked by their importance [44, 52, 95, 115]. Zhou and Wang [53] investigated critical ranking from two opposite aspects, i.e., vulnerability and potential, and found that the most vulnerable components may not be necessarily the most potential components. Baroud et al. [84] unified component importance by dividing it with the maximum importance. Azad et al. [70] defined increased cost as the sum of disruption cost and post-disruption recovery cost. The identification of critical combination of components was also studied in the literature [37, 41, 49]. Darayi et al. [62] and Whitman et al. [73] studied the component importance in multi-commodity networks. Dowds et al. [116] found that the critical ranking of components varies with levels of network resolution and demand aggregation. For road networks, especially highway networks, bridges are critical components. In case of limited budgets, resources should firstly be allocated to retrofit or recover bridges. Furthermore, the criticality among these bridges can be ranked due to their importance [18, 21, 22, 34, 36, 38, 48, 117].

### *B. Climate Change/Extreme Weather Events*

Global climate change and likely consequences such as sea level rise, floods and storms have increasingly threatened transportation systems. The resilience of transportation networks when facing extreme weather events (EWE) or long-term climate change has drawn considerate attention.

Stamos et al. [98] studied transportation modes transfer during EWE and used it to assess system's resilience. Testa et al. [31] used several topological indicators to measure the impact of EWE on coastal transportation networks. Espinet et al. [118] predicted the economic cost and damage of networks caused by temperature and precipitation increase. Shilling et al. [35] studied the exposure of State Road 37 in California to sea level rise. Zhu et al. [39, 50] assessed the resilience of metro and road network for Hurricanes Sandy and Irene. Alipour [117] investigated how to detect, quantify, and recover the damaged bridges in the aftermath of EWE. Asadabadi and Miller-Hooks [40] proposed several strategies to mitigate disruptions caused by sea level rise, and calculated reduced cost. Han et al. [119] forecasted the short-term and long-term impacts of 4-ft sea level rise in great Boston by 2030. Pregnolato et al. [120] proposed a function to relate flood depth and vehicle speed and found that by 2080s the disruptions caused by a 1-in-50-year event will increase by 66% in Newcastle.

## VII. Conclusions and Future directions

In this review, we provided a comprehensive review on resilient transportation systems. A systematic literature search method integrating database search, related journal search, and citation supplement was proposed to select all the appropriate articles. Based on the selected core papers, the definition of resilience was examined, and some related concepts were compared. We reviewed the metrics and mathematical models used to measure resilience, and the strategies used to enhance resilience in the literature. In each section, we divided the papers into different categories and summarized the main contributions in tables.

Furthermore, we summarize existing challenges and propose several potential research directions as follows.

### *A. Large-scale Transportation Networks*

One significant challenge is that most of the current methods can hardly be applied to large-scale transportation networks, especially optimization and simulation models. Topological methods are more efficient, while the characteristics of traffic flow are not captured in these models. There exists a trade-off between practicality and efficiency. Better integration of topological methods and flow-based methods could be explored. Data-driven methods can be another promising direction, while the ability of collecting adequate dynamic data and processing of these data rely on the technique advances in data analytics.

### *B. Multiple Objectives*

As discussed in section III, all the definitions in the literature describe the resilience of transportation systems from one or both of the following two perspectives: (1) the ability to maintain functionality under disruptions, and (2) time and resources required to restore performance level after disruptions. However, in the mathematical models to quantify resilience as listed in section IV, the recovery speed is mostly ignored. Merely considering finally restored performance level is not reasonable for service systems like transportation systems. Taking earthquake as an example, quick restoration of the transportation system means more relief goods being distributed and evacuees being saved. Recovering to an acceptable service level to meet fundamental evacuation requirements in the immediate aftermath should be prioritized in human lives involved systems. Thus, the objectives of the quantification or optimization models should be modified to this concern. In addition to performance level and recovery speed (time), economic cost should also be considered as one objective.

### *C. Social and Economic Perspectives*

All the previous studies are from the perspective of technology, such as maximizing performance loss, and recovery time. The impact of disasters on the society and economy should be investigated. For example, the suffering and recovery of the feelings of human beings can be studied. From the economic perspective, the recovery solutions should be subject to economic constraints, which will lead to multiple objectives as discussed above.

### *D. Resilience of Interdependent Systems*

Examples of interdependent transportation networks include integrated metro and bus service network, intermodal freight transport network, etc. The advantage of intermodal transportation networks is that traffic demand can be shared and transferred from one mode to another if disruption happens on one mode. However, high interdependence among different components in different systems can also encourage disruptions among different networks and lead to cascading failures. Future research could examine the methods that are able to improve the resilience of intermodal transportation networks while avoid cascading failure at the same time.

### *E. The Role of Human Beings in Recovery*

Almost all the resilience enhancement strategies are from the perspective of optimizing the utilization of resources. The role of human beings in the immediate response and long-term recovery is overlooked. Especially for those human centered systems, such as public transport systems, well pre-disruption training of users for mitigation of uncertainty and effective post-disruption response can significantly avoid failure spreading. However, the impacts of human beings are much harder to quantitatively investigate.

### *F. Demand Side Rebalancing Solutions*

In the current literature, rebalancing strategies have been proposed to increase the supply to accommodate the demands for transportation systems; few studies have been done from the perspective of decreasing demand. One method that we are working on is to collaboratively utilize supply and demand side strategies to generate a better rebalancing solution for emergency situations.

### G. *Resilience of the System vs Resilience in One Scenario*

One significant feature in the literature is that when measuring or enhancing the resilience of transportation systems, the level of disruption or the amount of resources available are usually pre-determined. That is to say, resilience is studied in certain specific scenarios. However, if resilience is regarded as an inherent property of a system, it should reflect the ability of the system in any potential scenarios. Thus, more comprehensive measurement methods should be proposed which are supposed to be independent of specific scenarios.

## REFERENCES


[1] R. Faturechi, and E. Miller-Hooks, “Measuring the Performance of Transportation Infrastructure Systems in Disasters: A Comprehensive Review,” *Journal of Infrastructure Systems,* vol. 21, no. 1, Mar, 2015.

[2] S. S. Chopra, T. Dillon, M. M. Bilec, and V. Khanna, “A network-based framework for assessing infrastructure resilience: a case study of the London metro system,” *Journal of the Royal Society Interface,* vol. 13, no. 118, May, 2016.

[3] C. S. Holling, “Resilience and stability of ecological systems,” *Annual review of ecology and systematics,* vol. 4, no. 1, pp. 1-23, 1973.

[4] Y. Sheffi, “The resilient enterprise: overcoming vulnerability for competitive advantage,” *MIT Press Books,* vol. 1, 2005.

[5] A. Rose, and S. Y. Liao, “Modeling regional economic resilience to disasters: A computable general equilibrium analysis of water service disruptions,” *Journal of Regional Science,* vol. 45, no. 1, pp. 75-112, 2005.

[6] W. N. Adger, “Social and ecological resilience: are they related?,” *Progress in human geography,* vol. 24, no. 3, pp. 347-364, 2000.

[7] E. Hollnagel, D. D. Woods, and N. Leveson, *Resilience engineering: Concepts and precepts*: Ashgate Publishing, Ltd., 2007.

[8] S. Hosseini, K. Barker, and J. E. Ramirez-Marquez, “A review of definitions and measures of system resilience,” *Reliability Engineering & System Safety,* vol. 145, pp. 47-61, 2016.

[9] J.W. Wang, R. R. Muddada, H. Wang, J. Ding, Y. Lin, C. Liu, and W. Zhang, “Toward a resilient holistic supply chain network system: Concept, review and future direction,” *IEEE Systems Journal,* vol. 10, no. 2, pp. 410-421, 2016.

[10] L. G. Mattsson, and E. Jenelius, “Vulnerability and resilience of transport systems - A discussion of recent research,” *Transportation Research Part a-Policy and Practice,* vol. 81, pp. 16-34, Nov, 2015.

[11] A. Reggiani, P. Nijkamp, and D. Lanzi, “Transport resilience and vulnerability: The role of connectivity,” *Transportation Research Part a-Policy and Practice,* vol. 81, pp. 4-15, Nov, 2015.

[12] M. Cao, "Transportation Resilience: A summative review on Definition and Connotation," *Proceedings of the 2015 International Conference on Automation, Mechanical Control and Computational Engineering*, Advances in Intelligent Systems Research A. Cheng and A. DeSouza, eds., pp. 1127-1132, 2015.

[13] C. Wan, Z. Yang, D. Zhang, X. Yan, and S. Fan, “Resilience in transportation systems: a systematic review and future directions,” *Transport Reviews*, pp. 1-20, 2017.

[14] C. Madhusudan, and G. Ganapathy, “Disaster resilience of transportation infrastructure and ports-An overview,” *International Journal of Geomatics and Geosciences,* vol. 2, no. 2, pp. 443, 2011.

[15] P. M. Murray-Tuite, "A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions." pp. 1398-1405.

[16] B. Berche, C. von Ferber, T. Holovatch, and Y. Holovatch, “Resilience of public transport networks against attacks,” *European Physical Journal B,* vol. 71, no. 1, pp. 125-137, Sep, 2009.

[17] C. Z. Liu, Y. Y. Fan, and F. Ordonez, “A two-stage stochastic programming model for transportation network protection,” *Computers & Operations Research,* vol. 36, no. 5, pp. 1582-1590, May, 2009.

[18] P. Bocchini, and D. M. Frangopol, “Optimal resilience-and cost-based postdisaster intervention prioritization for bridges along a highway segment,” *Journal of Bridge Engineering,* vol. 17, no. 1, pp. 117-129, 2010.

[19] J.W. Wang, W. Ip, and W.J. Zhang, “An integrated road construction and resource planning approach to the evacuation of victims from single source to multiple destinations,” *IEEE transactions on intelligent transportation systems,* vol. 11, no. 2, pp. 277-289, 2010.

[20] T. M. Adams, K. R. Bekkem, and E. J. Toledo-Durán, “Freight resilience measures,” *Journal of Transportation Engineering,* vol. 138, no. 11, pp. 1403-1409, 2012.

[21] P. Bocchini, and D. M. Frangopol, “Restoration of bridge networks after an earthquake: Multicriteria intervention optimization,” *Earthquake Spectra,* vol. 28, no. 2, pp. 426-455, 2012.

[22] L. Chang, F. Peng, Y. F. Ouyang, A. S. Elnashai, and B. F. Spencer, “Bridge Seismic Retrofit Program Planning to Maximize Postearthquake Transportation Network Capacity,” *Journal of Infrastructure Systems,* vol. 18, no. 2, pp. 75-88, Jun, 2012.

[23] M. O. Beiler, S. McNeil, D. Ames, and R. Gayley, “Identifying Resiliency Performance Measures for Megaregional Planning Case Study of the Transportation Corridor Between Boston, Massachusetts, and Washington, DC,” *Transportation Research Record*, no. 2397, pp. 153-160, 2013.

[24] J.W. Wang, H. Wang, W. Zhang, W. Ip, and K. Furuta, “Evacuation planning based on the contraflow technique with consideration of evacuation priorities and traffic setup time,” *IEEE transactions on intelligent transportation systems,* vol. 14, no. 1, pp. 480-485, 2013.

[25] R. Faturechi, E. Levenberg, and E. Miller-Hooks, “Evaluating and optimizing resilience of airport pavement networks,” *Computers & Operations Research,* vol. 43, pp. 335-348, 2014.

[26] R. Faturechi, and E. Miller-Hooks, “Travel time resilience of roadway networks under disaster,” *Transportation Research Part B-Methodological,* vol. 70, pp. 47-64, Dec, 2014.

[27] A. Osei-Asamoah, and N. E. Lownes, “Complex Network Method of Evaluating Resilience in Surface Transportation Networks,” *Transportation Research Record*, no. 2467, pp. 120-128, 2014.

[28] B. K. Bhavathrathan, and G. R. Patil, “Capacity uncertainty on urban road networks: A critical state and its applicability in resilience quantification,” *Computers Environment and Urban Systems,* vol. 54, pp. 108-118, Nov, 2015.

[29] B. K. Bhavathrathan, and G. R. Patil, “Quantifying resilience using a unique critical cost on road networks subject to recurring capacity disruptions,” *Transportmetrica a-Transport Science,* vol. 11, no. 9, pp. 836-855, Oct, 2015.

[30] S. Freiria, A. O. Tavares, and R. P. Juliao, “The Multiscale Importance of Road Segments in a Network Disruption Scenario: A Risk-Based Approach,” *Risk Analysis,* vol. 35, no. 3, pp. 484-500, Mar, 2015.

[31] A. C. Testa, M. N. Furtado, and A. Alipour, “Resilience of Coastal Transportation Networks Faced with Extreme Climatic Events,” *Transportation Research Record*, no. 2532, pp. 29-36, 2015.

[32] Y. O. Wang, H. C. Liu, K. Han, T. L. Friesz, and T. Yao, “Day-to-day congestion pricing and network resilience,” *Transportmetrica a-Transport Science,* vol. 11, no. 9, pp. 873-895, Oct, 2015.

[33] Q. Ye, and S. V. Ukkusuri, “Resilience as an Objective in the Optimal Reconstruction Sequence for Transportation Networks,” *Journal of Transportation Safety & Security,* vol. 7, no. 1, pp. 91-105, 2015.

[34] A. Alipour, and B. Shafei, “Seismic Resilience of Transportation Networks with Deteriorating Components,” *Journal of Structural Engineering,* vol. 142, no. 8, Aug, 2016.

[35] F. M. Shilling, J. Vandever, K. May, I. Gerhard, and R. Bregoff, “Adaptive Planning for Transportation Corridors Threatened by Sea Level Rise,” *Transportation Research Record*, no. 2599, pp. 9-16, 2016.

[36] A. Soltani-Sobh, K. Heaslip, P. Scarlatos, and E. Kaisar, “Reliability based pre-positioning of recovery centers for resilient transportation infrastructure,” *International Journal of Disaster Risk Reduction,* vol. 19, pp. 324-333, Oct, 2016.

[37] D. Z. W. Wang, H. X. Liu, W. Y. Szeto, and A. H. F. Chow, “Identification of critical combination of vulnerable links in transportation networks - a global optimisation approach,” *Transportmetrica a-Transport Science,* vol. 12, no. 4, pp. 346-365, Apr, 2016.

[38] W. L. Zhang, and N. Y. Wang, “Resilience-based risk mitigation for road networks,” *Structural Safety,* vol. 62, pp. 57-65, 2016.

[39] Y. Zhu, K. Ozbay, K. Xie, and H. Yang, “Using Big Data to Study Resilience of Taxi and Subway Trips for Hurricanes Sandy and Irene,” *Transportation Research Record*, no. 2599, pp. 70-80, 2016.

[40] A. Asadabadi, and E. Miller-Hooks, “Assessing strategies for protecting transportation infrastructure from an uncertain climate future,” *Transportation Research Part a-Policy and Practice,* vol. 105, pp. 27-41, Nov, 2017.

[41] S. A. Bagloee, M. Sarvi, B. Wolshon, and V. Dixit, “Identifying critical disruption scenarios and a global robustness index tailored to real life road networks,” *Transportation Research Part E-Logistics and Transportation Review,* vol. 98, pp. 60-81, Feb, 2017.

[42] B. Donovan, and D. B. Work, “Empirically quantifying city-scale transportation system resilience to extreme events,” *Transportation Research Part C-Emerging Technologies,* vol. 79, pp. 333-346, Jun, 2017.

[43] A. Kaviani, R. G. Thompson, and A. Rajabifard, “Improving regional road network resilience by optimised traffic guidance,” *Transportmetrica a-Transport Science,* vol. 13, no. 9, pp. 794-828, 2017.

[44] S. Kim, and H. Yeo, “Evaluating link criticality of road network based on the concept of macroscopic fundamental diagram,” *Transportmetrica a-Transport Science,* vol. 13, no. 2, pp. 162-193, 2017.

[45] M. Mojtahedi, S. Newton, and J. Von Meding, “Predicting the resilience of transport infrastructure to a natural disaster using Cox’s proportional hazards regression model,” *Natural Hazards,* vol. 85, no. 2, pp. 1119-1133, 2017.

[46] M. Nogal, A. O'Connor, B. Martinez-Pastor, and B. Caulfield, “Novel Probabilistic Resilience Assessment Framework of Transportation Networks against Extreme Weather Events,” *Asce-Asme Journal of Risk and Uncertainty in Engineering Systems Part a-Civil Engineering,* vol. 3, no. 3, Sep, 2017.

[47] J. M. Sadler, N. Haselden, K. Mellon, A. Hackel, V. Son, J. Mayfield, A. Blase, and J. L. Goodall, “Impact of Sea-Level Rise on Roadway Flooding in the Hampton Roads Region, Virginia,” *Journal of Infrastructure Systems,* vol. 23, no. 4, Dec, 2017.

[48] W. L. Zhang, N. Y. Wang, and C. Nicholson, “Resilience-based post-disaster recovery strategies for road-bridge networks,” *Structure and Infrastructure Engineering,* vol. 13, no. 11, pp. 1404-1413, 2017.

[49] Y. Zhou, J. B. Sheu, and J.W. Wang, “Robustness assessment of urban road network with consideration of multiple hazard events,” *Risk Analysis*, 2017.

[50] Y. Zhu, K. Xie, K. Ozbay, F. Zuo, and H. Yang, “Data-Driven Spatial Modeling for Quantifying Networkwide Resilience in the Aftermath of Hurricanes Irene and Sandy,” *Transportation Research Record*, no. 2604, pp. 9-18, 2017.

[51] N. Y. Aydin, H. S. Duzgun, F. Wenzel, and H. R. Heinimann, “Integration of stress testing with graph theory to assess the resilience of urban road networks under seismic hazards,” *Natural Hazards,* vol. 91, no. 1, pp. 37-68, Mar, 2018.

[52] S. C. Calvert, and M. Snelder, “A methodology for road traffic resilience analysis and review of related concepts,” *Transportmetrica a-Transport Science,* vol. 14, no. 1-2, pp. 130-154, 2018.

[53] Y. M. Zhou, and J. W. Wang, “Critical Link Analysis for Urban Transportation Systems,” *Ieee Transactions on Intelligent Transportation Systems,* vol. 19, no. 2, pp. 402-415, Feb, 2018.

[54] C. Ta, A. V. Goodchild, and K. Pitera, “Structuring a Definition of Resilience for the Freight Transportation System,” *Transportation Research Record*, no. 2097, pp. 19-25, 2009.

[55] R. Nair, H. Avetisyan, and E. Miller-Hooks, “Resilience framework for ports and other intermodal components,” *Transportation Research Record: Journal of the Transportation Research Board*, no. 2166, pp. 54-65, 2010.

[56] L. C. Chen, and E. Miller-Hooks, “Resilience: An Indicator of Recovery Capability in Intermodal Freight Transport,” *Transportation Science,* vol. 46, no. 1, pp. 109-123, Feb, 2012.

[57] E. Miller-Hooks, X. D. Zhang, and R. Faturechi, “Measuring and maximizing resilience of freight transportation networks,” *Computers & Operations Research,* vol. 39, no. 7, pp. 1633-1643, Jul, 2012.

[58] A. Abadi, and P. Ioannou, "Optimization strategies for resilient freight transport and sustainability." pp. 6472-6477.

[59] X. D. Zhang, and E. Miller-Hooks, “Scheduling Short-Term Recovery Activities to Maximize Transportation Network Resilience,” *Journal of Computing in Civil Engineering,* vol. 29, no. 6, Nov, 2015.

[60] A. John, Z. Yang, R. Riahi, and J. Wang, “A risk assessment approach to improve the resilience of a seaport system using Bayesian networks,” *Ocean Engineering,* vol. 111, pp. 136-147, 2016.

[61] H. Chen, K. Cullinane, and N. Liu, “Developing a model for measuring the resilience of a port-hinterland container transportation network,” *Transportation Research Part E-Logistics and Transportation Review,* vol. 97, pp. 282-301, Jan, 2017.

[62] M. Darayi, K. Barker, and J. R. Santos, “Component Importance Measures for Multi-Industry Vulnerability of a Freight Transportation Network,” *Networks & Spatial Economics,* vol. 17, no. 4, pp. 1111-1136, Dec, 2017.

[63] F. Fotuhi, and N. Huynh, “Reliable Intermodal Freight Network Expansion with Demand Uncertainties and Network Disruptions,” *Networks & Spatial Economics,* vol. 17, no. 2, pp. 405-433, Jun, 2017.

[64] A. Asadabadi, and E. Miller-Hooks, “Co-opetition in enhancing global port network resiliency: A multi-leader, common-follower game theoretic approach,” *Transportation Research Part B-Methodological,* vol. 108, pp. 281-298, Feb, 2018.

[65] A. Cox, F. Prager, and A. Rose, “Transportation security and the role of resilience: A foundation for operational metrics,” *Transport Policy,* vol. 18, no. 2, pp. 307-317, Mar, 2011.

[66] J. L. Bruyelle, C. O'Neill, E. M. El-Koursi, F. Hamelin, N. Sartori, and L. Khoudour, “Improving the resilience of metro vehicle and passengers for an effective emergency response to terrorist attacks,” *Safety Science,* vol. 62, pp. 37-45, Feb, 2014.

[67] L. Collis, F. Schmid, and A. Tobias, “Managing incidents in a complex system: a railway case study,” *Cognition Technology & Work,* vol. 16, no. 2, pp. 171-185, May, 2014.

[68] M. D'Lima, and F. Medda, “A new measure of resilience: An application to the London Underground,” *Transportation Research Part a-Policy and Practice,* vol. 81, pp. 35-46, Nov, 2015.

[69] K. Adjetey-Bahun, B. Birregah, E. Chatelet, and J. L. Planchet, “A model to quantify the resilience of mass railway transportation systems,” *Reliability Engineering & System Safety,* vol. 153, pp. 1-14, Sep, 2016.

[70] N. Azad, E. Hassini, and M. Verma, “Disruption risk management in railroad networks: An optimization-based methodology and a case study,” *Transportation Research Part B-Methodological,* vol. 85, pp. 70-88, Mar, 2016.

[71] R. Chan, and J. L. Schofer, “Measuring Transportation System Resilience: Response of Rail Transit to Weather Disruptions,” *Natural Hazards Review,* vol. 17, no. 1, Feb, 2016.

[72] J. Armstrong, J. Preston, and I. Hood, “Adapting railways to provide resilience and sustainability,” *Proceedings of the Institution of Civil Engineers-Engineering Sustainability,* vol. 170, no. 4, pp. 225-234, Aug, 2017.

[73] M. G. Whitman, K. Barker, J. Johansson, and M. Darayi, “Component importance for multi-commodity networks: Application in the Swedish railway,” *Computers & Industrial Engineering,* vol. 112, pp. 274-288, Oct, 2017.

[74] W. H. Ip, and D.W.Wang, “Resilience and Friability of Transportation Networks: Evaluation, Analysis and Optimization,” *Ieee Systems Journal,* vol. 5, no. 2, pp. 189-198, Jun, 2011.

[75] N. U. Serulle, K. Heaslip, B. Brady, W. C. Louisell, and J. Collura, “Resiliency of Transportation Network of Santo Domingo, Dominican Republic Case Study,” *Transportation Research Record*, no. 2234, pp. 22-30, 2011.

[76] D. Freckleton, K. Heaslip, W. Louisell, and J. Collura, “Evaluation of Resiliency of Transportation Networks After Disasters,” *Transportation Research Record*, no. 2284, pp. 109-116, 2012.

[77] P. Tamvakis, and Y. Xenidis, "Resilience in transportation systems," *Transport Research Arena 2012*, Procedia Social and Behavioral Sciences P. Papaioannou, ed., pp. 3441-3450, 2012.

[78] A. Reggiani, “Network resilience for transport security: Some methodological considerations,” *Transport Policy,* vol. 28, pp. 63-68, 2013.

[79] A. K. Hartmann, "Large-deviation properties of resilience of transportation networks," *European Physical Journal B,* vol. 87, no. 5, May, 2014.

[80] E. D. Vugrin, M. A. Turnquist, and N. J. K. Brown, "Optimal recovery sequencing for enhanced resilience and service restoration in transportation networks," *International Journal of Critical Infrastructures,* vol. 10, no. 3-4, pp. 218-246, 2014.

[81] X. Zhang, E. Miller-Hooks, and K. Denny, "Assessing the role of network topology in transportation network resilience," *Journal of Transport Geography,* vol. 46, pp. 35-45, Jun, 2015.

[82] M. Campo, H. Mayer, and J. Rovito, "Supporting secure and resilient inland waterways: evaluating off-loading capabilities at terminals during sudden catastrophic closures," *Transportation Research Record: Journal of the Transportation Research Board*, no. 2273, pp. 10-17, 2012.

[83] M. Omer, A. Mostashari, R. Nilchiani, and M. Mansouri, "A framework for assessing resiliency of maritime transportation systems," *Maritime Policy & Management,* vol. 39, no. 7, pp. 685-703, 2012.

[84] H. Baroud, K. Barker, J. E. Ramirez-Marquez, and C. M. Rocco, "Importance measures for inland waterway network resilience," *Transportation Research Part E-Logistics and Transportation Review,* vol. 62, pp. 55-67, Feb, 2014.

[85] H. Baroud, J. E. Ramirez-Marquez, K. Barker, and C. M. Rocco, "Stochastic Measures of Network Resilience: Applications to Waterway Commodity Flows," *Risk Analysis,* vol. 34, no. 7, pp. 1317-1335, Jul, 2014.

[86] H. Baroud, K. Barker, J. E. Ramirez-Marquez, and C. M. Rocco, "Inherent costs and interdependent impacts of infrastructure network resilience," *Risk Analysis,* vol. 35, no. 4, pp. 642-662, 2015.

[87] N. Farhadi, S. A. Parr, K. N. Mitchell, and B. Wolshon, "Use of Nationwide Automatic Identification System Data to Quantify Resiliency of Marine Transportation Systems," *Transportation Research Record*, no. 2549, pp. 9-18, 2016.

[88] S. Hosseini, and K. Barker, "Modeling infrastructure resilience using Bayesian networks: A case study of inland waterway ports," *Computers & Industrial Engineering,* vol. 93, pp. 252-266, Mar, 2016.

[89] M. Janic, "Modelling the resilience, friability and costs of an air transport network affected by a large-scale disruptive event," *Transportation Research Part a-Policy and Practice,* vol. 71, pp. 1-16, Jan, 2015.

[90] S. H. Stroeve, B. A. van Doorn, and M. H. C. Everdij, "Analysis of the roles of pilots and controllers in the resilience of air traffic management," *Safety Science,* vol. 76, pp. 215-227, Jul, 2015.

[91] S. Belkoura, J. M. Pena, and M. Zanin, "Generation and recovery of airborne delays in air transport," *Transportation Research Part C-Emerging Technologies,* vol. 69, pp. 436-450, Aug, 2016.

[92] S. Dunn, and S. M. Wilkinson, "Increasing the resilience of air traffic networks using a network graph theory approach," *Transportation Research Part E-Logistics and Transportation Review,* vol. 90, pp. 39-50, Jun, 2016.

[93] E. Filippone, F. Gargiulo, A. Errico, V. Di Vito, and D. Pascarella, "Resilience management problem in ATM systems as a shortest path problem," *Journal of Air Transport Management,* vol. 56, pp. 57-65, Sep, 2016.

[94] S. Yoo, and H. Yeo, "Evaluation of the resilience of air transportation network with adaptive capacity," *International Journal of Urban Sciences,* vol. 20, pp. 38-49, 2016.

[95] A. Voltes-Dorta, H. Rodriguez-Deniz, and P. Suau-Sanchez, "Vulnerability of the European air transport network to major airport closures from the perspective of passenger delays: Ranking the most critical airports," *Transportation Research Part a-Policy and Practice,* vol. 96, pp. 119-145, Feb, 2017.

[96] L. A. Schintler, R. Kulkarni, S. Gorman, and R. Stough, "Using raster-based GIS and graph theory to analyze complex networks," *Networks and Spatial Economics,* vol. 7, no. 4, pp. 301-313, 2007.

[97] J. G. Jin, L. C. Tang, L. J. Sun, and D. H. Lee, "Enhancing metro network resilience via localized integration with bus services," *Transportation Research Part E-Logistics and Transportation Review,* vol. 63, pp. 17-30, Mar, 2014.

[98] I. Stamos, E. Mitsakis, J. M. Salanova, and G. Aifadopoulou, "Impact assessment of extreme weather events on transport networks: A data-driven approach," *Transportation Research Part D-Transport and Environment,* vol. 34, pp. 168-178, Jan, 2015.

[99] A. Marzuoli, E. Boidot, P. Colomar, M. Guerpillon, E. Feron, A. Bayen, and M. Hansen, "Improving Disruption Management With Multimodal Collaborative Decision-Making: A Case Study of the Asiana Crash and Lessons Learned," *Ieee Transactions on Intelligent Transportation Systems,* vol. 17, no. 10, pp. 2699-2717, Oct, 2016.

[100] W. Hua, and G. P. Ong, "Network survivability and recoverability in urban rail transit systems under disruption," *Iet Intelligent Transport Systems,* vol. 11, no. 10, pp. 641-648, Dec, 2017.

[101] T.-Y. Liao, T.-Y. Hu, and Y.-N. Ko, "A resilience optimization model for transportation networks under disasters," *Natural Hazards*, pp. 1-21, 2018.

[102] S. Mudigonda, K. Ozbay, and B. Bartin, "Evaluating the resilience and recovery of public transit system using big data: Case study from New Jersey," *Journal of Transportation Safety & Security*, pp. 1-29, 2018.

[103] R. Twumasi-Boakye, and J. O. Sobanjo, "Resilience of Regional Transportation Networks Subjected to Hazard-Induced Bridge Damages," *Journal of Transportation Engineering, Part A: Systems,* vol. 144, no. 10, pp. 04018062, 2018.

[104] M. Bababeik, N. Khademi, and A. Chen, "Increasing the resilience level of a vulnerable rail network: The strategy of location and allocation of emergency relief trains," *Transportation Research Part E: Logistics and Transportation Review,* vol. 119, pp. 110-128, 2018.

[105] M. Janić, "Modelling the resilience of rail passenger transport networks affected by large-scale disruptive events: the case of HSR (high speed rail)," *Transportation*, pp. 1-37, 2018.

[106] K. L. Clark, U. Bhatia, E. A. Kodra, and A. R. Ganguly, "Resilience of the US National Airspace System Airport Network," *IEEE Transactions on Intelligent Transportation Systems*, 2018.

[107] D. Henry, and J. E. Ramirez-Marquez, "Generic metrics and quantitative approaches for system resilience as a function of time," *Reliability Engineering & System Safety,* vol. 99, pp. 114-122, 2012.

[108] P. Bocchini, D. M. Frangopol, T. Ummenhofer, and T. Zinke, "Resilience and sustainability of civil infrastructure: Toward a unified approach," *Journal of Infrastructure Systems,* vol. 20, no. 2, pp. 04014004, 2013.

[109] M. Bruneau, S. E. Chang, R. T. Eguchi, G. C. Lee, T. D. O'Rourke, A. M. Reinhorn, M. Shinozuka, K. Tierney, W. A. Wallace, and D. Von Winterfeldt, "A framework to quantitatively assess and enhance the seismic resilience of communities," *Earthquake spectra,* vol. 19, no. 4, pp. 733-752, 2003.

[110] K. Tierney, and M. Bruneau, "Conceptualizing and measuring resilience: A key to disaster loss reduction," *TR news*, no. 250, 2007.

[111] A. Rose, "Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions," *Environmental Hazards,* vol. 7, no. 4, pp. 383-398, 2007.

[112] Y. M. Zhou, and J. W. Wang, "Efficiency of complex networks under failures and attacks: a percolation approach," *Physica A*, 2018.

[113] K. Heaslip, W. Louisell, and J. Collura, *A methodology to evaluate transportation resiliency for regional networks*, 2009.

[114] B. P. Y. Loo, and K. Y. K. Leung, "Transport resilience: The Occupy Central Movement in Hong Kong from another perspective," *Transportation Research Part a-Policy and Practice,* vol. 106, pp. 100-115, Dec, 2017.

[115] A. A. Khaled, M. Z. Jin, D. B. Clarke, and M. A. Hogue, "Train design and routing optimization for evaluating criticality of freight railroad infrastructures," *Transportation Research Part B-Methodological,* vol. 71, pp. 71-84, Jan, 2015.

[116] J. Dowds, K. Sentoff, J. L. Sullivan, and L. Aultman-Hall, "Impacts of Model Resolution on Transportation Network Criticality Rankings," *Transportation Research Record*, no. 2653, pp. 93-100, 2017.

[117] A. Alipour, "Enhancing Resilience of Bridges to Extreme Events by Rapid Damage Assessment and Response Strategies," *Transportation Research Record: Journal of the Transportation Research Board*, no. 2604, pp. 54-62, 2017.

[118] X. Espinet, A. Schweikert, N. van den Heever, and P. Chinowsky, "Planning resilient roads for the future environment and climate change: Quantifying the vulnerability of the primary transport infrastructure system in Mexico," *Transport Policy,* vol. 50, pp. 78-86, Aug, 2016.

[119] Y. F. Han, P. C. Zegras, V. Rocco, M. Dowd, and M. Murga, “When the Tides Come, Where Will We Go? Modeling the Impacts of Sea Level Rise on the Greater Boston, Massachusetts, Transport and Land Use System,” *Transportation Research Record*, no. 2653, pp. 54-64, 2017.

[120] M. Pregnolato, A. Ford, V. Glenis, S. Wilkinson, and R. Dawson, “Impact of Climate Change on Disruption to Urban Transport Networks from Pluvial Flooding,” *Journal of Infrastructure Systems,* vol. 23, no. 4, Dec, 2017.

[121] J. W.Wang, R.L.Dou, R.R. Muddada, and W.J.Zhang, “Management of a holistic supply chain network for proactive resilience: theory and case study,” *Computers & Industrial Engineering,* vol. 125, pp. 668-677, 2017.

[122] R. Raj, J.W.Wang, A.Nayak, M.K.Tiwari, B.Han, C.L.Liu, and W.J. Zhang, "Measuring resilience of supply chain systems using a survival model", *IEEE Systems Journal*, vol.9, no. 2, pp. 377-381.

[123] J.W. Wang, W.H.Ip, R.R.Muddada, J.L.Huang, and W.J.Zhang, "On Petri Net implementation of proactive resilient holistic supply chain networks," *International Journal of Advanced Manufacturing Technology*, vl.69no.1-4, pp.427-437.

[124] G.Y. Xu, J.W. Wang, G.Q. Huang, and C.H, Chen, "Data-driven resilient fleet management for cloud asset-enabled urban flood control," *IEEE Transactions on Intelligent Transportation Systems*, vol.19, no. 6, pp.1827-1838.

[125] J.W.Wang, H.F.Wang, Y.M.Zhou, Y. Wang, and W.J.Zhang, " On an integrated approach to resilient transportation systems in emergency situations," *Natural computing*, doi:10.1007/s11047-016-9605-y.


**Yaoming Zhou** was born in Jiangsu, China, in 1992. He received the B.Eng. degree in mechatronics from Zhejiang University, Hangzhou, China, in 2014 and the Ph.D in operations research from The University of Hong Kong, Hong Kong.

His research interests include modeling and analysis of transportation systems, and the integration of operations research, data analytics, and artificial intelligence and their application to transportation.

**Junwei Wang** received the Ph.D. degree in mechanical engineering from the University of Saskatchewan, Saskatoon, SK, Canada, in 2013 and the Ph.D. degree in systems engineering from the Northeastern University, Shenyang, China, in 2006. From 2011 to 2013, he was a Japan Society for the Promotion of Science Postdoctoral Fellow with the Department of Systems Innovation, School of Engineering, The University of Tokyo, Tokyo, Japan. Since March 2014, he has been an Assistant Professor with the Department of Industrial and Manufacturing Systems Engineering, Faculty of Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong. He is the author or coauthor of more than 60 refereed journal papers and refereed conference papers, and a coauthor of a book on optimization algorithms. His current research interests include modeling and optimization, service systems engineering, and resilience engineering.

**Hai Yang** received the Ph.D. degree from Kyoto University, Japan. He is currently a Chair Professor in the Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology. He is internationally known as an active scholar in the field of transportation, with more than 210 papers published in SCI/SSCI indexed journals and an H-index citation rate of 43. In recognition of his outstanding research, Prof. Yang has received a number of national and international awards, including JSCE Outstanding Paper Award (1991), Distinguished Overseas Young Investigator Award from the National Natural Science Foundation of China (NSFC) (2004), National Natural Science Award bestowed by the State Council of PR China (2011), HKUST School of Engineering Research Excellence Awards (2012). He is an elected permanent member of the International Advisory Committee of the prestigious International Symposium on Transportation and Traffic Theory (ISTTT). Prof. Yang served as editors/guest editors or editorial advisory board members for a number of international journals. He is now the Editor-in-Chief of Transportation Research Part B: Methodological, a top journal in the field of transportation.