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Resilience in transportation systems: a systematic review and future directions

Chengpeng Wan[a,b,c], Zaili Yang[c], Di Zhang[a,b], Xinping Yan[a,b] and Shiqi Fan[a,b]

[a]Intelligent Transportation Systems Research Center, Wuhan University of Technology, Wuhan, People's Republic of China; [b]National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, Wuhan, People's Republic of China; [c]Liverpool Logistic Offshore & Marine Research Institute, Liverpool John Moores University, Liverpool, UK

ABSTRACT

The Belt and Road (B&R) initiative was introduced by the Chinese government to promote the worldwide economic development and multilateral cooperation between China and the associated countries. As a crucial part of global supply chains, transportation plays a key role to ensure the implementation of the B&R. Safety is one of the issues with great importance in transportation research. However, its foci have been expanded from traditional risk through security to resilience and sustainability. Resilience has attracted considerable interests from both researchers and practitioners across different research domains in recent years. Various studies have been conducted on transportation resilience from different perspectives. Consequently, different definitions have been developed to define and describe resilience. This paper presents a systematic review on transportation resilience with emphasis on its definitions, characteristics, and research methods applied in different transportation systems/contexts. It aims to figure out what transportation resilience is and what kind of essential characters it usually has. More importantly, research challenges are analysed and a future research agenda on the resilience of transportation systems is proposed. This paper will provide comprehensive insights into understanding the transportation resilience, as well as establish new horizons for relevant research topics within the context of the B&R.

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1. Introduction

In 2013, the concept of "the Silk Road Economic Belt and 21st-Century Maritime Silk Road" (also referred to as "the Belt and Road", B&R) was promoted as a new way to motivate regional cooperation on international trade (Swaine, 2015). Since then, a lot of efforts have been made to accelerate its development. The B&R has been designed to enhance the flow of economic factors and the efficient allocation of resources, in order to promote the multilateral cooperation as well as development between China and the

CONTACT Di Zhang zhangdi@whut.edu.cn Intelligent Transportation Systems Research Center and National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, Wuhan 430063, People's Republic of China

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associated countries along the B&R, especially those from Asia, Europe, and Africa. Furthermore, the "Vision and Actions on Jointly Building the Silk Road Economic Belt and 21st-Century Maritime Silk Road" was issued on March 2015 (Xu, 2015) to outline the principles, framework, cooperation priorities, and cooperation mechanisms of the B&R. Based on five main international transportation routes proposed in the "Vision and Actions", six international economic cooperation corridors are designed to build connectivity and partnerships among the countries involved in the B&R. These economic corridors are (1) New Eurasian Land Bridge, (2) China–Mongolia–Russia Corridor, (3) China–Central Asia–West Asia Corridor, (4) China–Indochina Peninsula Corridor, (5) China–Pakistan Corridor, and (6) Bangladesh–China–India–Myanmar Corridor, as represented in Figure 1.

The development of the B&R initiative has also promoted the construction of transportation infrastructure such as seaports, dry ports, and railways, both inside and outside China, which further benefits international logistics service and global supply chains, especially the service provided by multimodal transportation systems. Safety, as a crucial part in daily transportation operations, has always been one of the most important issues, attracting a lot of attention from both academia and industries.

Nowadays, due to the increasing complexity and uncertainty in global trade, transportation systems are often exposed to the risks from a multiplicity of disruptions, ranging from natural disasters, such as earthquakes, tsunamis, and hurricanes, to man-made hazardous events like terrorist attacks and strikes. In 1995, the Kobe earthquake in Japan resulted in total economic losses of $150 billion, with more than $100 billion losses caused by infrastructure and property damages and around $50 billion losses from economic disruptions (Omer, Mostashari, Nilchiani, & Mansouri, 2012). The costs of the 11-day workers' strike happened in the U.S. in 2002 were estimated at around $2 billion per day due to the lockout of 29 West Coast ports (Omer et al., 2012). A series of terrorist suicide bomb attacks in London in July 2005 killed 52 and injured more than 700. It also resulted in

Figure 1. Six economic corridors proposed by B&R. Source: China-Britain Business Council (2015).

a reduction of 22.7 million London underground passenger journeys in the following four months (Prager, Beeler Asay, Lee, & von Winterfeldt, 2011). In 2011, Hurricane Irene struck the East Coast of the U.S., causing at least 56 deaths and nearly $15.6 billion losses. More than 500 miles of highways, 2000 miles of roadways, and 200 miles of railways in Vermont were affected (Faturechi & Miller-Hooks, 2014b). The interdependency among different transportation systems further intensifies the damages from these disruptive events. Therefore, the research foci in terms of transportation safety have been expanded from traditional risk through security, and to resilience and sustainability in recent years.

Since the B&R was originally proposed to facilitate international trade and promote regional cooperation, much attention is drawn on transportation systems. A resilient transportation system plays a key role in offering accessibility to resources and supporting reliable and efficient supply chains, which is essential for freight transport and the implementation of the B&R initiative. Besides, a modern integrated transportation system is composed of different modes that are usually managed by different authorities and their associated infrastructures may be allocated in different countries, which can form a new dimension of possible vulnerabilities. Thus, a comprehensive analysis on the transportation resilience is necessary and significant for the implementation of B&R. Moreover, as a new initiative, there is not much relevant literature, thus, reviewing the past studies of transportation resilience can help to point out the new research directions in the future development of B&R.

Resilience is commonly used to describe the ability of an entity or system to bounce back to a normal condition after its original state being affected by a disruptive event (Henry & Emmanuel Ramirez-Marquez, 2012). Since resilience was first introduced in the context of ecological systems by Holling (1973), its concept has been gradually developed and then applied to the fields of psychology (e.g. Dent and Cameron, 2003), economics (e.g. Rose, 2007), and engineering (e.g. Hollnagel, Woods, & Leveson, 2007). Regarding the research of resilience in transportation areas, a number of studies have been carried out with a focus on different segments of transportation systems such as helicopter transportation (Gomes, Woods, Carvalho, Huber, & Borges, 2009), inland ports (Hosseini & Barker, 2016), railway transportation networks (Ip & Wang, 2011), and public transportation (Berche, von Ferber, Holovatch, & Holovatch, 2009). Meanwhile, there are also numerous studies conducted from a perspective of the whole transportation system, for example, Nair, Avetisyan, and Miller-Hooks (2010), Chen and Miller-Hooks (2012), and Miller-Hooks, Zhang, and Faturechi (2012), to name but a few. This paper aims to provide a comprehensive overview of the previous research, with emphasis on the definition and key characteristics of transportation resilience. It will yield an archive of recent literature on the studied topic and offer researchers with the background information needed to support the continuity of the relevant research in the area. In addition, the analysis results, particularly the research challenges, will provide helpful insights and future research agenda for building and managing resilience in transportation for both academics and practitioners.

The rest of the paper is structured as follows. Section 2 introduces the approach to intensively review the relevant studies and evaluates the results in terms of the distribution of literature by years of publication, journals, and research methods. Section 3 highlights the main features of definitions of transportation resilience, and Section 4 describes its key characteristics and expounds them using a system performance schematic. The conclusion and suggestions for future research on resilience within the context of B&R are provided in Section 5.

2. Methodology of review

To carry out a comprehensive review of resilience studies in the transportation domain, a systematic procedure for searching and selecting the reviewed articles has been applied, by referring to Tukamuhabwa, Stevenson, Busby, and Zorzini (2015). The procedure is composed of three steps: (i) online database searching, (ii) article screening, and (iii) final refining and analysing. In systematically selecting the papers for review in our study, we used the Web of Science (Core Collection) database, one of the most comprehensive multidisciplinary content search platforms for academic research (Hosseini, Barker, & Ramirez-Marquez, 2016), to identify the relevant papers. Search strings such as "resilient transportation system", "resilient transportation network", "transportation resilience", "resilience in transportation system" and "resilience in transportation network" (as well as substrings of these terms) were selected as "Topic" items to conduct the searching work, with a time span from 2005 to 2015. All the search results generated from the above strings were then combined with the "OR" function. The search was completed in November 2015. A total of 232 papers were retrieved.

The screening process was conducted in two stages to ensure the quality and relevance of the reviewed papers. To begin with, our study was limited to only peer-reviewed academic journals, as peer-review process is the most guaranteed one for the acceptance of the scientific community (Bergström, van Winsen, & Henriqson, 2015). In this way, conference proceedings, editorial materials, and book chapters were deliberately excluded from our examination. This reduced the number of articles from 232 to 147. In the second stage, titles, keywords, and abstracts were checked to ensure the articles were relevant to the study of resilience in the transportation field, and consequently 83 articles remained.

In the final step, these articles were further refined through full-text review. This is important due to the fact that in some articles, resilience was regarded only as subtopics or just as a label, where more efforts were made on other topics such as system safety management and disaster response. Besides, articles that addressed the resilience from a pure logistics management or a purely mathematical perspective, for example, the impacts of network structures on resilience, were also excluded.[1] To serve for the potential improvement of transportation in global supply chains and international logistics networks, we selected those papers relevant to the definitions, measurement, modelling, or applications of resilience in the transportation field. Although the studies conducted on both freight and passenger transport are taken into consideration in this paper, the majority are associated with the freight transport. Finally, the result formed a total database of 61 peer-reviewed academic journal papers (see Supplementary 1). The distribution of literature by years of publication, journals, and research methods were generated, and the information from these sources was analysed in depth in terms of the definitions of resilience and their characteristics in the transportation field. It is noted that none of them are relevant to B&R given the initiative is still in an infant stage. However, such a thorough review will be valuable in identification of research challenges on transportation resilience and hence provide useful insights in terms of ensuring resilience of transportation systems related to B&R studies.

2.1 Distribution by year of publication

According to the database composed of 61 academic journal articles, their distribution by year from 2005 to November 2015 is represented in Figure 2 (In fact, it appears that articles in our database dated from 2009, which revealed the fact that transportation resilience as an independent subject, was systematically developed recently). Although the contemporary academic use of resilience started as early as several decades ago in ecology and psychology (Flach, 1988; Walker, Holling, Carpenter, & Kinzig, 2004), its application and development in the transportation field are relatively late. However, its popularity in the transportation field also shows an increasing trend in recent years, like other disciplines, evidenced by Bergström et al. (2015).

2.2 Distribution by journals

Several different journals that published works related to resilience in a transportation context were included in our literature review. Table 1 lists top 10 journals that contribute the most (e.g. more than two articles) in this literature review. Among them, Transportation Research Record is the most significant source of articles related to the research on transportation resilience, contributing seven articles alone. *Reliability Engineering and*

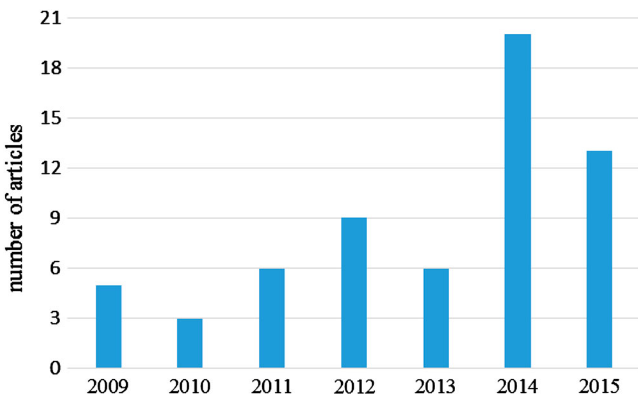

Figure 2. Distribution of papers by year of publication, by November 2015.

Table 1. Top journal sources of resilience in the transportation field.

No.	Journal title	No. of articles
1	*Transportation Research Record*	7
2	*Reliability Engineering and Systems Safety*	6
3	*Risk Analysis*	4
4	*Transportation Research-Part A*	4
5	*Transportation Research-Part E*	3
6	*European Physical Journal B*	3
7	*Transportation Research-Part B*	2
8	*IEEE Systems Journal*	2
9	*Transport Policy*	2
10	*Maritime Policy and Management*	2

Systems Safety, *Risk Analysis*, *Transportation Research-Part A*, *Transportation Research-Part E*, and *European Physical Journal B* are the followers. Other applications of resilience in transportation are mainly published in *Transportation Research-Part B*, *IEEE Systems Journal*, *Transport Policy*, and *Maritime Policy and Management*. Theses journals together account for more than half of the reviewed articles. It can be seen from Table 1 that most of these journals have a strong background in research of transportation or risk/safety disciplines.

2.3 Distribution by research methods

The dominant research methods chosen for these studies are based on surveys, case studies, conceptual work, mathematical modelling, simulation, and others (e.g. Sachan & Datta, 2005; Tukamuhabwa et al., 2015; Wacker, 1998; Woo, Pettit, Kwak, & Beresford, 2011). A survey aims to study the sampling of individual units on a specific topic. It is a commonly used method to collect required information which generally can be done through the questionnaire and the interview. A case study is an in-depth investigation of a particular person, community, or situation. Research conducted through surveys or case studies belongs to empirical research (Tukamuhabwa et al., 2015). The conceptual work category here is rather broad, including analysis on concept issues such as definitions, properties, theoretical framework, and conceptual modelling. While, being different to the conceptual modelling, papers under mathematical modelling refer to those applying mathematical concepts and language to describe and represent objective reality. A simulation method is used to study the operation of a real-world or a theoretical process/system under various preset circumstances for different purposes (e.g. numerical testing, observing behaviour, optimising performance, or exploration of new states). The category of "others" encompasses archival analysis, literature review, and perspectives from industries. The distribution of papers based on different research methods is depicted in Figure 3. Empirical studies are further analysed in Table 2 in order to provide helpful insights for the potential applications of resilience in practice.

From Figure 3, it can be seen that mathematical modelling is the dominant research method, accounting for 57.3% of the selected works on transportation resilience in our

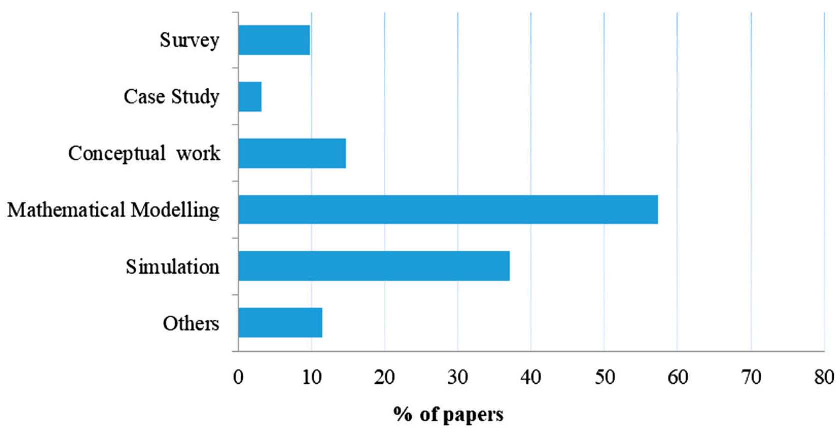

Figure 3. Categorisation of papers based on research methods.

Table 2. Overview of empirical research on transportation resilience.

Author(s)	Year	Country	Methodology	Application fields	Research objectives	Disturbances
Gomes et al.	2009	Brazil	Survey	Helicopter transportation	To discover transport system resilience in terms of workload demands and economic pressures	Constraints of daily operations
Berle et al.	2011	U.S.A. and Panama	Survey	Maritime transportation	To provide matrices of the key functions of maritime transportation systems	Failures
Adams et al.	2012	U.S.A.	Case study	Road transportation	To present a set of criteria to qualify the computed resilience measures	Disruptive weather events
Nursey-Bray et al.	2013	Australia	Survey	Port	To evaluate and learn from practices relating to climate change preparedness within Australian ports	Climate change
Bruyelle et al.	2014	U.K.	Case study	Metro system	To propose improvements to the design of metro systems, and to improve the management of emergency situations	Terrorist attacks
Chang et al.	2014	Canada	Survey	Infrastructure system	To develop a practice approach to characterise communities' infrastructure vulnerability and resilience in disasters	Earthquake & flood
Becker et al.	2015	U.S.A.	Survey	Port	To investigate how port stakeholders consider impacts of storms on seaport's vulnerability, and address the concerns	Storm
Becker & Caldwell	2015	U.S.A.	Survey	Port	To identify strategies that can improve port's resilience from a practice perspective	Storm

study, followed by simulation, which has been applied in more than one-third of the total research. Also, it should be noted that the majority of the studies using mix-methods (e.g. Refs [2], [4]–[7], [10], [15], and [16] in Supplementary 1) are those utilising mathematical modelling and simulation simultaneously, where simulation methods are commonly used as a validation of the proposed mathematical models. Conceptual work makes up 14.7% of the total, most of which attempted to develop a framework for analysing transportation resilience, proposed suitable metrics for its measurement, as well as provided reference for resilient strategies made from a systematic perspective. Survey and case study methods, which are usually used to gain insights from empirical research through capturing participants' perceptions and investigating real-life cases, have not been broadly used in transportation resilience studies, visible in only 9.8% and 3.2% of the investigated publications, respectively. Seven papers belong to "others", five of which are literature reviews (i.e. Refs [22], [33], [38], [40], and [49] in Supplementary 1). Regarding the literature review work, Refs [22] and [38] discussed resilience of transportation systems in face of natural disasters, while Ref [33] investigated the resilience of urban surface transport to climate change. Ref [40] reviewed the transport system vulnerability and analysed its relationship with resilience. More emphasis was put on two main streams studying transport vulnerability, which was based on transport network topology and transport system supply and demand principals, respectively. Ref [49] proposed a research agenda for resilience engineering (RE) based on literature review, in which only aviation and railway domains were considered. Among all these articles, 70.49% of them are conducted using quantitative assessment approaches, as shown in Figure 4.

The number of empirical studies – surveys and case studies – is limited to eight, as presented in Table 2. These empirical works are mainly conducted through surveys, with data collected from interviews or workshops of operators, authorities, and stakeholders on particular disturbances to transport systems. Obviously, it reveals a research challenge, lack of empirical data when conducting transportation resilience study within the context of B&R. Natural hazards are identified as predominant sources of external disturbances, for specific, climate change as well as disruptive weather events such as storms, earthquakes, and floods. Only two case studies can be found in terms of the selected academic publications. They are conducted to evaluate the resilience of a metro system and road transportation, respectively. One case study from Bruyelle et al. (2014) tried to enhance the resilience of metro vehicles in the case of terrorist attacks through improving emergency

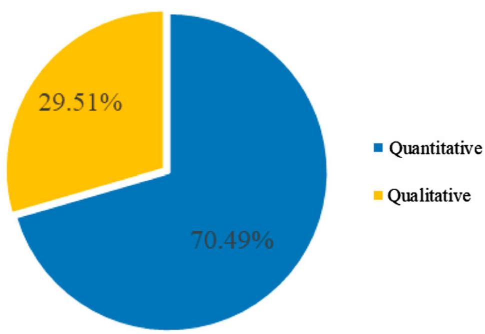

Figure 4. Ratio of research papers conducted through quantitative and qualitative methods.

responses and assisting evacuation and rescue. The man-made attacks of 7 July 2005 London bombing were revisited with consideration of cooperation, social identity, information, and communication. In another case study, Adams, Bekkem, and Toledo-Durán (2012) estimated the resilience of roadway transportation from two dimensions (which are reduction and recovery) that derived from the resilience triangles used in disaster research (Bruneau et al., 2003). Several sections along the Interstate 90/94 corridor from Hudson to Beloit, Wisconsin, were selected, and the variations of sampled truck speeds and counts during blizzards and flooding in 2008 were observed and analysed to quantitatively characterise their resilience response. Regarding the research fields, it is obvious that ports have attracted most of the attention from researchers, accounting for almost half of the empirical research. This is no wonder because of the irreplaceable role a port plays in the international trade, being a critical intermodal node. Other empirical studies are conducted from a system level, such as infrastructure systems, maritime transportation systems, and metro systems. Moreover, most of the empirical work has been done in the developed countries, prominently in the U.S.A. and the U.K. (e.g. Becker & Caldwell, 2015; Becker, Matson, Fischer, & Mastrandrea, 2015; Berle, Rice, & Asbjørnslett, 2011; Bruyelle et al., 2014). However, developing countries are usually more vulnerable to disruptions due to the limited availability of resources supporting their response to emergency situations and the development of infrastructure, such as road transport networks (Tukamuhabwa et al., 2015). Overall, the lack of empirical research on transportation resilience indicates an insufficient understanding on how we can create and maintain transportation resilience in general and urge an emerging research issue on the development of resilience transport systems to ensure the successes of B&R in specific.

3. Definitions of resilience in the transportation field

Currently, there are a number of different opinions and definitions of resilience in various application domains. For example, National Infrastructure Advisory Council (NIAC) (2009) defined the resilience of an infrastructure system as its ability to predict, absorb, adapt, and/or quickly recover from a disruptive event such as natural disasters. In social science research, Adger (2000) defined social resilience as an ability of communities to deal with external stresses and disturbances resulting from social, political, and environmental changes. In an engineering context, Hollnagel et al. (2007) defined resilience as the inherent ability of a system to alter its functionality in the face of unexpected changes (Hosseini et al., 2016), to name just a few.

From the perspective of transportation, various types of research on resilience have also been conducted, aiming to figure out what the transportation resilience is, what kind of features a resilient transportation system has, and what capabilities it should have. As a result, there are a variety of definitions for the notion of resilience proposed, though some of them are similar, having overlaps with other relevant concepts such as reliability, vulnerability, robustness, and survivability. The definitions applied by previous transportation-related studies are summarised in Supplementary 2.

Even though the research foci of these studies are transportation systems, they are conducted from different perspectives. Some focus on the resilience of the whole generalised transportation systems or networks, while others concentrate on a specified system like roadway, maritime, or railway transportation systems. Moreover, most of the definitions of transportation resilience are given either from a system perspective or a network perspective. A careful review of definitions of resilience shows that there is no universal description on what the transportation resilience is or what the standard definition it should be. However, the most similarities and differences can be observed across these resilience definitions. The highlights of resilience definitions from previous transportation-related studies are summarised as below. New thoughts are generated as far as the transportation resilience study on B&R is concerned.

i. The majority of the research defines resilience as a kind of ability (or capability) of a system/network, belonging to a system/network's inherent nature, while other few researchers (e.g. Baroud, Barker, Ramirez-Marquez, & Rocco, 2014b; Mansouri, Nilchiani, & Mostashari, 2009) define it as a function which can be used as a metrics to measure systems' performance against potential disruptions.

   Thoughts: Resilience can be quantified as either a capability or a function measuring performance. Therefore, research on the use of a quantitative index to describe transportation resilience in B&R should be encouraged for the purpose of self- or cross-benchmark of investigated systems, particularly those from different regions and countries. It will also be very beneficial to justify the investment on new infrastructure through cost–benefit analysis, since the improvement of resilience is quantified as the immediate benefit.

ii. Almost all these definitions are given with a consideration of abnormal conditions such as shocks, disturbances, disruptions, or even disasters. This reveals that one of the core intentions of resilience is the performance of a system in face of disruptive events.

   Thoughts: The disruptions refer to at large, hazards, threats, and nature disasters/climate risks. Traditional risk analysis techniques dealing with hazards will probably be insufficient, triggering the employment of advanced uncertainty modelling in transportation resilience in the B&R.

iii. The main difference in terms of resilience definitions lies in the verbs (such as resist, absorb, maintain, and withstand) used to describe the performance of a system when a disruptive event occurs. Among all the actions, "recovery" is considered as a critical one, although it has been presented in different forms, such as "revive from", "carry out recovery activities", and "recover from". Besides, it is worth noting that in some definitions, the authors suggested to take the time and costs a system needs to recover into consideration (e.g. Haimes, 2009; Mansouri, Nilchiani, & Mostashari, 2010).

   Thoughts: Unlike the relatively standardised parameters used to estimate traditional risk (e.g. likelihood and consequence), resilience involves a wide range of attributes in its evaluation, which are often not easily adoptable when the studied scenarios change. It may be one of the reasons why similarities exist among different terminologies being used (e.g. resist, maintain, and withstand). Besides, the description of system performance highlights the importance of transportation resilience in both pre- and post-disruptions. It provides useful insights for the management of daily operations before a disruption and emergency management of transportation systems after a disruption under the B&R background.

iv. Definitions from some authors like Venkittaraman and Banerjee (2014) and Omer et al. (2012) emphasised that it is necessary for a system to return back to a pre-disaster state or at least be close to it, while definitions from other researchers do not require the system to do so.

Thoughts: It reflects two ways of understanding resilience. One regards resilience as the property of a system to keep near to a stable equilibrium point, while the other refers to the ability to transform from one equilibrium state to another, emphasising more on its dynamic characteristics. This will result in different ways of measuring and managing transportation resilience. In practice, it is noteworthy that cost–benefit analysis looks promising to justify suitable control measures under different situations when applying resilience management to the development of transport infrastructure in B&R.

Based on the review of the above references, here, we refer transportation resilience as the ability of a transportation system to absorb disturbances, maintain its basic structure and function, and recover to a required level of service within an acceptable time and costs after being affected by disruptions.

4. Key characteristics of resilience

Different terms have been used to describe the resilience and its characteristics, including but not limited to vulnerability (e.g. Omer et al., 2012; Zhang, Miller-Hooks, & Denny, 2015), adaptability (e.g. Becker & Caldwell, 2015), robustness (e.g. Blockley, Godfrey, & Agarwal, 2012), preparedness (e.g. Miller-Hooks et al., 2012), redundancy (e.g. Berle et al., 2011), response (e.g. DiPietro, Scott Matthews, & Hendrickson, 2014), and recovery (e.g. Adams et al., 2012; Venkittaraman & Banerjee, 2014). It is quite often the case that the same term is explained from various perspectives and used in a variety of ways to address different requirements. Moreover, researchers sometimes introduce new terminologies for similar concepts. Currently, there are scarce studies analysing the similarity and difference of the application of such terms in the transportation area. Here, we extracted from the literature the most commonly used terms when describing the features and connotations of resilience, as summarised in Table 3.

As a cross-disciplinary concept, resilience has been studied in different research fields from various aspects with emphasis on one or several of its certain properties. Sometimes it is not sufficient to describe resilience by only using mathematical equations, especially in a more general situation. It will increase the difficulty for decision-makers to understand and apply it in practice and inevitably result in the neglect of parts of its properties in theoretical research. Thus, this study concludes and expounds the key characteristics of resilience by using graphic perspective.

Hypothetical system performance of curves under the normal condition and in face of disruptive event is shown in Figure 5. It attempts to incorporate as many characteristics of resilience mentioned in the literature as possible and provides a general overview of performance of a time-dependent system. For a transport system, the performance can be understood as the service function it offers, and it is usually measured with operational metrics such as components' capacity, traffic flow, and throughput. Overall, the performance with respect to the occurrence time of disruptive

Table 3. Interpretations and analysis of terms related to resilience.

Term	Interpretation/analysis	References
Vulnerability	It is defined as the susceptibility to damage or perturbation – especially where small damage or perturbation leads to disproportionate consequences. It is also regarded as the property of a transportation system which may weaken or constrain its ability to endure, handle, and survive threats and disruptive events that originated both within and outside the system boundaries.	Asbjørnslett and Rausand (1999); Blockley et al. (2012)
Adaptability (or adaptive capacity)	It is defined as one of the functions of a resilient system, reflecting its flexible ability to response to new pressures. Its main features lie in response to changes reflecting the dynamic nature of complex systems.	Bhamra, Dani, and Burnard (2011); Dalziell and McManus (2004); Fiksel (2003)
Robustness	It is the property of being strong, healthy, and hardy. Thus, it is generally defined as the ability to withstand or absorb disturbances and remain intact when exposed to disruptions.	Blockley et al. (2012); Faturechi and Miller-Hooks (2014b)
Flexibility	It is the ability of a system to respond to shocks and adjust itself to changes through contingency planning after disruptions. It is also referred to as an ability to reconfigure resources as well as to cope with uncertainties. As such, connotations of flexibility are opposite to that of robustness which emphasises the ability to endure these changes rather than to adapt to them.	Berle, Norstad, and Asbjørnslett (2013); Cox, Prager, and Rose (2011); Faturechi and Miller-Hooks (2014a); Goetz and Szyliowicz (1997)
Reliability	It is generally defined as the probability that a network remains operative given the occurrence of a disruption event. It can be either a pre- or post-disruption metric for measuring system performance.	Barker et al. (2013); Faturechi and Miller-Hooks (2014a);
Recoverability (or the ability to recover)	It has been discussed the most in terms of the research of transportation resilience. It is defined as the ability of a network to recover functionality in a timely manner. It is regarded to as an important feature of secure and highly functioning transport networks.	Baroud et al. (2014a)
Redundancy	It indicates the ability of certain components of a system to take over the functions of failed components without adversely affecting the performance of the system itself. In the context of transportation, redundancy is generally viewed as the existence of optional routes between origins and destinations. It is commonly accepted that the more redundancy a system has, the more resilient it will be.	Haimes (2009); Fiksel (2003); Tukamuhabwa et al. (2015); Omer et al. (2012)
Survivability	It is generally defined as the ability to withstand sudden disturbances while meeting original demands. Survivability techniques have been considered as an access to mitigating the vulnerability of a network or system.	Baroud et al. (2014a); Faturechi and Miller-Hooks (2014b)
Preparedness	It refers to "prepare certain measures before disruption happens", and it enhances the resilience of a system by lessening potential negative impacts from disruptive events. It can be subdivided as emergency preparedness and response preparedness.	Berle et al. (2011); Jin, Tang, Sun, and Lee (2014)
Resourcefulness	Resourcefulness is defined as the availability of materials, supplies, and crews to restore functionality in a study of transportation	Adams et al. (2012); Francis and Bekera (2014); Reggiani (2013)

(*Continued*)

Table 3. Continued.

Term	Interpretation/analysis	References
	resilience. Resourcefulness was treated as one of stabilising measures in resilience. It indicates the level of preparedness in effectively resisting an adverse event.	
Responsiveness	It is regarded as an important factor to the resilience of transportation networks. Similar to redundancy, responsiveness factors of a system may also increase the costs although it is able to improve the service level of a system.	Klibi, Martel, and Guitouni (2010); Ivanov, Sokolov, and Dolgui (2014)
Rapidity	It is a well-studied concept in the "resilience triangle", a framework that has been applied in civil infrastructure for decades. It contains a hidden meaning of recovery, but with more emphasis on the speed to recover. It affects the duration of reduced performance of a system.	Adams et al. (2012); Dorbritz (2011).

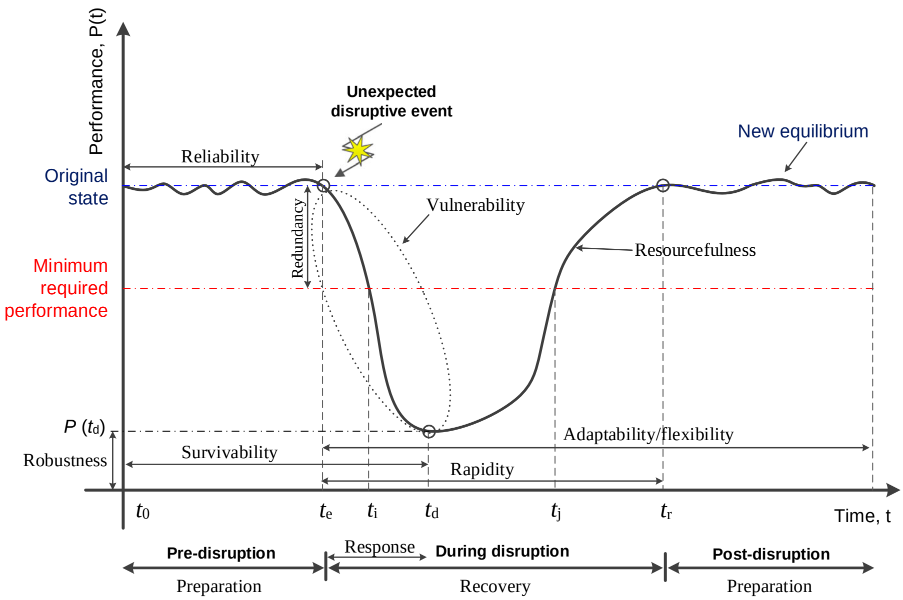

Figure 5. Schematic of performance of a resilient system. It is newly developed by the authors with reference to Enjalbert et al. (2011), Dorbritz (2011), Baroud et al. (2014a), and Shafieezadeh and Ivey Burden (2014).

event can be divided into three stages: pre-disruption (t_0, t_e), disruption (t_e, t_r), and post-disruption ($t > t_r$) periods.

In the pre-disruption stage, the system operates in an original state as planned, where both the system capacity and demand are not affected. It is a normal condition of a transport system/network that begins at the reference time t_0, and ends when a disruptive event occurs at time t_e. This period of time is dominated by reliability which enables the system to perform with required service function for a certain period of time without failing and provides the baseline of performance at the original state (Baroud, Barker, Ramirez-Marquez, & Rocco, 2014a).

System performance declines once the disruptive event occurs at time t_e. Usually, it will drop to the threshold value where the transport system merely meets the lowest requirements, and then, the degradation continues until time t_d, when the negative effects from the disruptive event are fully released. Here, the system performance researches its worst situation. The system responds immediately at the moment it is affected, in order to mitigate disruption and positively influence its spreading process during its impacts. Recovery strategies are involved to rebuild system accessibility and regain its functionality as fast as possible. In this stage, both robustness and redundancy impact the initial reduction of the system performance. However, the former characteristic decides where the lowest point is, while the latter one determines the difference between original and threshold value of performance. In transportation fields, redundancy is also viewed as the existence of optional routes between origins and destinations, which can help to mitigate adverse impacts of disasters to a transportation network. Vulnerability in this study refers to the physical sensitivity of the system to disruptions, influencing the degradation speed of its performance. The shape of system performance curve during disruption is affected by resourcefulness with two important aspects to be considered, that are, the access to the resource and protection of the resource. This characteristic is significant in the designing and planning of a transport system/network. Rapidity and recoverability are similar in terms of the recovery from disruptions, while rapidity emphasises on the speed to achieve so, and thus it has an impact on the duration of reduced system performance.

After time t_r, the system stabilises to another acceptable performance level, and therefore, a new cycle of system performance begins. It should be noted that the new equilibrium can be different (either an improved state or partial recovered state) compared to the original state before disruptions, according to the requirements. Preparation, as a kind of strategy that is crucial for transportation planning, can be incorporated before a disruption to enhance the redundancy and resourcefulness of a system. Also, experience from previous disruptions (if there is any) will contribute to the preparation of the following possible disruptive events.

Based on the above analysis, it is reckoned that four primary characteristics that a resilient transportation system should possess in general are reliability, redundancy, robustness, and recoverability (4R), as these attributes dominantly determine the overall performance of a transportation system on how long it can perform without failing, what actions it will take in the face of a disruptive event, how much function it will remain after being disrupted, and how it reaches a new equilibrium.

5. Conclusion and future research directions in B&R research

This paper provides a comprehensive review of the available literature on resilience in the transportation context based on the 61 academic journal papers identified from a systematic review procedure. Analysis of the empirical studies, different definitions of resilience, and various characteristics being used to describe the features of resilience are carried out in order to provide helpful solutions to the questions on what resilience is, what characteristics it should have, and how to build and manage resilience in the transportation field. More importantly, based on the analysis, research challenges and useful remarks on resilience evaluation and control in transport systems of the B&R can be developed. Based on the review of current research of resilience in the transportation area, some research challenges as well as future agenda are discussed as follows.

i. Defining and applying contextual resilience

As the literature review presents, there is no universal and widely accepted definition of resilience yet. We argue that, as an interdisciplinary concept, it is extremely difficult, if not impossible, and fruitless to strive for a universally accepted definition of resilience, and resilience should be utilised in different ways depending on specific applications at hand. However, it is still essential and significant to propose a specific definition of resilience to define its study scope, research methods, and required data before applying it within certain domains, such as disaster resilience and climate change resilience. Furthermore, it will be important to select proper and suitable elements/characteristics to describe or construct the contextual resilience for specific cases (e.g. B&R). This will provide more useful insights for practitioners and policy-makers to promote the application of resilience in practice when developing the B&R. In return, practical experiences from industries will promote the development of resilience-related theories, enriching its connotations.

ii. Developing new evaluation frameworks for resilience assessment

This will offer a useful guidance for the quantitative assessment of transportation resilience with reasonable and practical procedures. It is necessary for the proposed framework to incorporate the features of transportation resilience, involve various segments of a transportation system, consider the different phases of a disturbance striking the system, connect resilience with safety management, and properly deal with both qualitative and quantitative inputs. Since the B&R initiative will greatly facilitate the development of transportation infrastructure across China and the associated countries, strengthening the connectivity among them through multimodal transportation systems (Zhao, 2016), more attention needs to be put on the application of resilience in the early design of the associated infrastructure. Although some resilience frameworks in other disciplines have already been studied for many years, such as the R4 Framework for assessing seismic resilience of communities (Bruneau et al., 2003) and a framework for the design of a sustainable industrial enterprise (Fiksel, 2003), relevant research in the transportation field is still in its infancy. It is required to enable this framework not only to assess the resilience status of existing transportation systems to find out vulnerable parts and prepare for the unpredictable disasters during the implication of the B&R but also in the system design process, to provide a reference for the optimal decision-making for the development of transport infrastructure of B&R, on issues such as route planning, and key infrastructure maintenance and renewal.

iii. Incorporating advanced uncertainty methods into resilience assessment

According to the B&R initiative, one main maritime shipping route across South China Sea has been proposed, starting from Quanzhou (China) to Venice (Italy), via Fuzhou, Guangzhou, Haikou, Hanoi, Kuala Lumpur, Jakarta, Colombo, Calcutta, Nairobi, and Athens. At least nine countries are involved into this trade route, which complicates the maritime transportation system, and increases the difficulty to enhance its resilience. As current conditions of safety and standards for safety management usually vary among different countries, it will be challenging to meet the requirements from every incorporated management authorities at the same time. Besides, other obstacles lie in the collection of data from different companies, ships, ports, and organisations, as well as processing of multi-source information, such as the fusion of data with different units, features, or dimensions. Moreover, conflicts and uncertainties may exist (Aven & Zio, 2011), further increasing the difficulties to deal with the collected information. Therefore, advanced methods need to be introduced, such as fuzzy theory (Adjetey-Bahun, Birregah, Châtelet, & Planchet, 2016), Bayesian networks (Hosseini & Barker, 2016), and evidential reasoning approach (Zhang, Yan, Zhang, Yang, & Wang, 2016), to enable the resilience assessment of B&R-related projects in uncertainty operational environment, where traditional assessment methods are lacking full capability.

iv. Measuring vulnerability of transport network components

In the design and management of transportation networks, it is crucial to understand which components are most important to the performance of the whole network, and thus vulnerable when facing disturbances. Although it is widely studied in reliability engineering, few studies have been found to measure the vulnerability of components considering the resilience of the whole transportation networks (Barker, Ramirez-Marquez, & Rocco, 2013; Baroud et al., 2014a). Measuring the vulnerability of transport network components (coupled with cost–benefit analysis) will provide helpful reference for the decision of better investment in the B&R-related projects, and for the optimal distribution of limited resources in processes of both emergency preparedness and response to those inevitable disasters. For example, 15 seaports alongside the southeast coast of China (e.g. Shanghai Port, Tianjin Port, and Guangzhou Port) have been presented in the B&R initiative as the basic nodes to build a safe and efficient maritime transport networks. These 15 ports are of significance due to their superior geographic locations. However, their influence on the resilience of the whole transport network involving seaports from other countries is still unclear. Thus, research from a network perspective using methods such as centrality measures and graph theory, as well as simulation techniques will be beneficial. The challenge lies in that vulnerabilities of transport systems are significantly affected by, and hence normally coupled with, specific disruptions. The issues as to how to integrate the vulnerability of the analysed nodes and the possible disruptions they face remain unclear.

v. Achieving the sustainable development of the B&R initiative

In recent years, the increasing number of low-frequency high-impact disruptive events such as malevolent attacks, and natural disasters has diverted research effort on safety from traditional risk-based approaches to resilience-based methods. Among the others, a well-defined and applied concept that has been discussed together with resilience is sustainability. According to Blockley et al. (2012), resilience is logically regarded as necessary but not sufficient for sustainability, which implies a stricter requirement needed to achieve the sustainability of a system. Generally, they both reflect a system's ability to survive in face of disruptive events, while the sustainability focuses on a longer term performance (Fiksel, 2003). This is important to the long-term development of B&R initiative under an implicated and volatile international environment. We should understand the impacts from those external factors. For example, the increasing melting of ice in Arctic water has made it a potential option route for merchant vessels. Will Arctic navigation be of any threat and challenge to the development of B&R, or serve as a complementary contribution towards its establishment?

The above challenges, which are developed through the analysis of the investigated articles, presents a picture of research agenda for future work on transportation resilience particularly within the context of B&R developments.

Note

1. The main aim of this study is to investigate the definitions, features, and characteristics of transportation resilience. Pure mathematical analyses on resilience with little relevant information are therefore excluded.

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