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Critical review

Resilience of urban transportation systems. Concept, characteristics, and methods.

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ABSTRACT

Urban transportation systems are susceptible to disturbances, interruptions, and risks from natural and human causes. The concept of resilience has been introduced into urban transportation systems to reduce the consequences of its disruptions. Recently, this concept has attracted considerable interest from researchers from different areas of transportation and mobility. However, several investigations about this issue were carried out under different perspectives, resulting in a more comprehensive concept, which includes adapting and transforming systems for different levels of equilibrium. This article provides a thorough and conceptual review of resilience applied to urban transportation systems focusing on its definitions, characteristics, and quantification methods. Based on this, the evaluation of the level of resilience of mobility subsystems is discussed to provide the basic framework for generating a tool to assess the resilience of the urban transportation system.

1. Introduction

The growth of large cities and metropolitan areas around the world presents challenges to urban transportation systems. In fact, in large cities, there has been a huge increase in transportation demand given the growing mobility needs of the resident population (Dunphy and Fisher, 1996). Urbanization is a key issue in the economic development of cities, regions and even countries. Cities cover only about 2% of the planet's surface, however, they account for about 75% of the world's resource consumption (Madlener and Sunak, 2011). Associated with this growth, urban mobility patterns are dominated by private cars, leading to an increase in road traffic, and causing mobility problems such as congestion, environmental pollution, noise, and traffic accidents (Farahani et al., 2013).

Traffic congestion directly affects the quality of urban mobility services, such as the movement of people and goods, which reduces the levels of accessibility and urban mobility. Additionally, it contributes to increasing delays and energy expenditure (Ko et al., 2017), pollution and stress (Bigazzi et al., 2015; Bastos et al., 2019), which in turn decreases productivity and leads to higher living costs for society (Rao and Rao, 2012). Thus, governments and transport authorities need to adequately plan transportation networks and control traffic movements to ensure and mitigate problems related to mobility (Samimi and Mohammadian, 2010; Farahani et al., 2013; Moriarty, 2016).

Urban transportation systems are always exposed to different types of disturbances. Disruptions that may affect the functioning of the urban transportation system are the same as those affecting other urban systems in general, e.g. natural disasters such as hurricanes, floods, fires, or human-made events such as terrorist attacks, cultural events, strikes and system failures caused by human error or mismanagement (Suarez et al., 2005; Koetse and Rietveld, 2009; Bollinger et al., 2014; Cao, 2015; Pregnolato et al., 2017). Thus, the concept of resilience is a timeline topic of interest in transportation systems due due to the increase of the exposure to extreme events in our cities such as massive traffic congestions and natural disasters (Nemry and Demirel, 2012; Wamsler et al., 2013; Markolf et al., 2019; Pregnolato et al., 2019). This exposure is related to the continuous sprawling and uncontrolled land use occupation of cities, as well as the increase o population and its territorial complexity, observing that cities vulnerability and criticality to future extreme events and disasters increases (Borde et al., 2007; Stamos et al., 2015).

The concept of resilience was firstly introduced in a study on ecological systems by Holling (1973), defining the ability of these systems to absorb and maintain changes in environmental variables. However, resilience in transportation systems is not a consensual concept as different researchers have a variety of backgrounds, perspectives, and

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[1] Contribution of the authors as mentioned below with their responsibility in the research.

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Table 1
Definition of Resilience of Transportation Systems.

Definition	Research area	Author(s)
"Resilience is a characteristic that indicates system performance under unusual conditions, recovery speed, and the amount of outside assistance required for restoration to its original functional state."	Transportation Systems	((Murray-Tuite, 2006, p.1398)
"…Resilience is defined as the ability of the system to absorb the consequences of disruptions to reduce the impacts of disruptions and maintain freight mobility."	Freight Transportation Systems	(Ta et al., 2009, p.21)
Resilience is defined as the expected fraction of demand that can be met post-disaster.	Freight Transportation systems	(Miller-Hooks et al., 2012)
"…the resilience of supply…" is *"…defined as the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at desired levels of connectedness and control over structure and function."*	Freight Transportation systems	(Spiegler et al., 2012, p.6182)
"The definition of resiliency … is the ability for a transportation network to absorb disruptive events gracefully and return itself to a level of service equal to or greater than the pre-disruption level of service within a reasonable time frame."	Transportation Infrastructures	(Freckleton et al., 2012, p.110)
"Resilience deals with the response of the system in the face of shock and its ability to continue to provide the expected service delivery levels."	Road Transportation systems	(Omer et al., 2013, p.389)
"Resilient transportation systems enable quick evacuation, rescue, distribution of relief supplies, and other activities for reducing the impact of natural disasters and for accelerating the recovery from them."	Transportation Systems	(Osogami et al., 2013, p.1)
"It appears that resilience, conceived of as the capacity/ability of the system to absorb shocks without catastrophic changes in its basic functional organisation, is a potentially effective tool in understanding the evolutionary paths of complex spatial networks, such as transport and communication networks."	Transportation Systems	(Reggiani, 2013, p.67)
"Resilience of a system refers to the ability to withstand disruptions within acceptable reduction in-service performance."	Railway transportation systems	(Jin et al., 2014, P.17)
"Resilience is the speed at which a system returns to equilibrium after a disturbance away from equilibrium."	Railway Transportation Systems	(D'Lima and Medda, 2015, p.38)
"The concept of resilience is intended to capture a system's capacity to maintain its function after a major disruption or disaster."	Transportation Systems	(Mattsson and Jenelius, 2015, 31)
The authors *"…have defined resilience as the ability of transportation systems to experience a potentially damaging event and return to a healthy state of operations in a reasonable period of time after that event."*	Railway Transportation Systems	(Chan and Schofer, 2016, p.7)
The authors *"… 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."*	Transportation Systems	(Wan et al., 2017, p.11)

understandings on this issue.

Planning and management transport authorities aim to promote more resilient urban transportation systems in order to avoid potential losses and obstructions to the movement of people and goods, as well as permanent damage to infrastructure. Thus, this article aims to deconstruct the concept, analyse the dimensions and identify the main characteristics of the resilience of an urban transportation system. To this end, a holistic review is presented aiming to define a general and comprehensive framework to support and encompass a future model for evaluating urban transportation system resilience in order to provide a set of basic and supportive knowledge frameworks for technical staff, policymakers and the scientific community in general.

Furthermore, this review also intends to identify the main methods used to measure and/or improve resilience in transportation systems, thus providing the basis for scientific and technical analysis of resilience to be used mainly by researchers to develop future assessment tools.

This article has the following structure: Section 1 briefly presents the issue of urban transportation resilience and describes the main objectives of this research. Section 2 provides a summary of the research methodology in this review. Section 3 explores the concept of the resilience of transportation systems. In Section 4, the main characteristics of urban transportation systems resilience are described. Section 5 is presented a discussion about the characteristics of vulnerability and reliability against resilience. Section 6 summarises the application of the resilience concept in different types of urban transportation systems. In Section 7, the main methods used to measure and/or improve urban transportation system resilience are described in detail. Section 8 presents the strengths, weaknesses and trends for future research on the resilience of urban transportation systems. Finally, in Section 9, the main conclusions of this research are presented.

2. Research methodology

This work identifies and systematically analyses the relevant literature regarding the resilience of transportation systems. Thus, it was adopted a procedure that comprised four phases (Pawson et al., 2005; Ribeiro and Pena Jardim Gonçalves, 2019). Phase 1 consisted of gathering literature through an extensive search using three databases, *Web of Science (SCOPUS)*, *Google Scholar* and *Web of Knowledge (Clarivate Analytics)*, which are considered the most comprehensive and reliable scientific research databases (Hosseini et al., 2016). During phase 2 were applied the following criteria to include and exclude results:

- General keywords, such as "Resilience of transportation systems", "Resilient urban systems", "Resilience of urban transportation systems", "Resilient transportation systems" and "Resilient transportation" were used;
- Were only selected articles published over the last 20 years (from 1999 to 2019) once the majority of the works related with this concept were published during this period of time, ensuring a sample with a good time coverage for this review exercise;
- Were only selected articles published in journals indexed in *Clarivate Analytics* and/or *Scopus* databases because the revision process is considered more rigorous and the acceptance from the scientific community is ensured (Bergström et al., 2015);
- Were only selected articles with more than 10 citations, except for 2018 and 2019 since these were recently published.

After an initial scan of publications, in phase 3 a snowballing technique was adopted whereby additional literature was identified through the citations made in each publication (Van Wee and Banister, 2016). After completing these three phases, 79 scientific articles were obtained. In the final phase, phase 4, to increase the feasibility of this review process it was narrowed the article selection. Therefore, the articles found in phase 2 were revisited and analysed their contents in depth. This phase was done once in some articles, the resilience was only considered as a subtopic or merely a label where the focus was on other topics, such as system security, risk management and disaster response. After completing all phases, this methodology resulted in 74 articles.

Finally, these articles were analysed and studied in-depth, especially

concerning issues related to the definitions, characteristics and evaluation tools of resilience in urban transportation systems.

3. The resilience of urban transportation systems

By analysing the state of the art, an increase in the number of studies in the transportation sector that addresses this issue of resilience can be observed in recent years. The main objective of these investigations was found to be centred on defining the concept, type of resources and the characteristics that a transportation system must have to be resilient. In Table 1, several definitions of transportation system resilience found in the literature are presented. There are also a high number of definitions for this specific area (transportation systems), although some of them are very similar.

Some authors focus on the resilience of the transportation system in general (Murray-Tuite, 2006; Osogami et al., 2013; Mattsson and Jenelius, 2015; Wan et al., 2017), while others focus on the resilience of a specific transportation system, such as railway (Jin et al., 2014; D'Lima and Medda, 2015; Chan and Schofer, 2016), road (Omer et al., 2013) or even, in more specific cases, freight transportation (Ta et al., 2009; Miller-Hooks et al., 2012; Spiegler et al., 2012). Yet, some authors apply the resilience concept at the level of the infrastructures (Freckleton et al., 2012) and not to the entire system.

All definitions presented in Table 1 associate the concept of the resilience of the transportation system with adverse conditions, abnormal conditions or disturbances that may influence the normal functioning or the equilibrium of the transportation systems. The main differences found in the definitions of the resilience of transportation systems lie in actions that a system can perform to face disturbances/perturbations. Thus, the evaluation of resilience of transportation systems can integrate the following actions: resist (Jin et al., 2014), absorb (Ta et al., 2009; Freckleton et al., 2012; Reggiani, 2013), maintain (Mattsson and Jenelius, 2015), recover (Spiegler et al., 2012; D'Lima and Medda, 2015; Chan and Schofer, 2016), reduce (Osogami et al., 2013) the impacts of a disruptive event or disturbance (shock (Reggiani, 2013), disaster (Osogami et al., 2013; Mattsson and Jenelius, 2015) or interruption (Ta et al., 2009; Spiegler et al., 2012)) that influence the performance (service level (Murray-Tuite, 2006; Freckleton et al., 2012; Omer et al., 2013; Jin et al., 2014)) provided by the system.

It should also be noted that some definitions take into account the recovery time considered acceptable (Murray-Tuite, 2006; Freckleton et al., 2012; Chan and Schofer, 2016) to restore the normal operating conditions of the transportation systems.

However, from the literature, it can also be seen that some studies divided resilience into two categories: static and dynamic (Rose, 2007; Pant et al., 2014; Uday and Marais, 2015; Chen and Rose, 2018).

According to Chen and Rose (2018), based on Rose (2007), static and dynamic resilience in economic systems can be defined as:

- Static resilience – "… *is the ability to maintain the operation of a system, while the economic counterpart is utilizing remaining resources as efficiently as possible in order to maintain the function performance of the system. This reflects the core of the economic problem based on how to best use scarce resources*";
- Dynamic resilience – "… *refers to the ability and speed of recovery, where the economic counterpart pertains to investing wisely in repair and reconstruction. This is a dynamic consideration from the standpoint of economics because it involves a time trade-off diverting resources for investment represents setting aside current consumption to enhance productivity at future times.*"

According to Amoaning-Yankson and Amekudzi-Kennedy (2017) and Deloukas and Apostolopoulou (2017), in transportation systems, static resilience is related to its robustness, in order to maintain the system operating after a shock or hazard occurs without immediate system infrastructure restoration. In turn, dynamic resilience in transportation systems aims to re-establish the initial level of performance and operation as quickly as possible after the occurrence of a disaster. Thus, resilience in transportation systems is not only supported in the action of preventing a system failure against a perturbation, but it also refers to, if necessary, the capacity and ability of the system to adapt and reduce the impact and to avoid a catastrophic partial or entire failure of the system.

Along these lines, Cox et al. (2011) selected and defined specific categories to static and dynamic transportation systems resilience. Thus, static resilience strategies include conservation, input substitution, inventories, excess capacity, relocation resource unimportance, import substitution, export substitution, technological change, production recapture, and logistics refinement. On the other hand, dynamic resilience strategies to increase speed recovery include: removing operating impediments, management effectiveness, speeding restoration, input substitution, import-substitution, and inventories (Cox et al., 2011).

These strategies were defined to improve the system and to be implemented by other system authorities or customers (e.g., firms and individuals) (Cox et al., 2011). In summary, static resilience is related to the strength of the system and dynamic resilience to the time of recovery during a disturbance.

Thus, in the specific area of transportation, it can be concluded that the aim of studying resilience is to figure out methodologies to measure transportation resilience, to evaluate the level of transportation system resilience under different interruptions, and to identify critical points (segment or intersection), from which countermeasures can be devised to reduce the impacts, within a static and/or dynamic framework.

Finally, after analysing the conceptual definition of the resilience of a transportation system, four main actions (basic dimensions) of the resilience of transportation systems were identified: resist, recover, absorb and transform.

Based on all the definitions presented in Table 1, the following definition is proposed for the resilience of urban transportation systems: the ability of a system to resist, reduce and absorb the impacts of a disturbance (shock, interruption, or disaster), maintaining an acceptable level of service (static resilience), and restoring the regular and balanced operation within a reasonable period of time and cost (dynamic resilience).

4. Main characteristics of the resilience of urban transportation systems

There are many characteristics related to resilience such as adaptation, robustness, preparedness, interdependence, efficiency, rapidity and redundancy. However, sometimes the same term is used in different ways to meet different requirements, according to different perspectives. Table 2 presents a summary of the characteristics found in the literature to describe the resilience of urban transportation systems, as well as the set of variables used to quantify its characteristics.

According to the literature, some of the resilience studies are based on characteristics of the "triangle of resilience" created by Bruneau et al. (2003) (Bocchini and Frangopol, 2012; Adjetey-Bahun et al., 2014; Zobel and Khansa, 2014; Ukkusuri, 2015; Alice and Behrouz, 2016; Zhang and Wang, 2016; Leobons et al., 2019). The "triangle of resilience" was mainly used to measure the community's resilience to seismic activities. This triangle represents the loss of infrastructure functionalities and disruptions, as well as the pattern of restructuring and recovery over time, relying on the 4 Rs framework: Robustness, Redundancy, Resources and Rapidity (Bruneau et al., 2003). Thus, there is a relation between the community systems and the transportation systems, since one system directly affects the other and vice-versa. Redundancy, robustness and adaptation are the most used characteristics in the literature to define the concept of resilience. Redundancy and robustness are more related to transportation infrastructures, and adaptation with transportation systems. Overall, these

Table 2
Main characteristics in the resilience of urban transportation systems.

Characteristic	Description	Variables	Author(s)
Redundancy	Redundancy is the capacity of some components of a system to take over the functions of failed components without impairing the performance of the system itself.	Characteristics of the system: - Traffic flows; - Network size; - Land users; - Number of transportation modes. - Geographic location of the elements of the network; Performance variables: - Capacity of the elements that make up the Network; - Travel time; - Travel distance; - Travel costs	(Ta et al., 2009; Berche et al., 2009; Leu et al., 2010; Chen and Miller-Hooks, 2011; Cox et al., 2011; Freckleton et al., 2012; Jenelius and Mattsson, 2012; Miller-Hooks et al., 2012; Tamvakis and Xenidis, 2012; Bocchini and Frangopol, 2012; Lhomme et al., 2013; Omer et al., 2013; Osogami et al., 2013; Barker et al., 2013; Adjetey-Bahun et al., 2014; Faturechi and Miller-Hooks, 2014; Jin et al., 2014; Azadeh et al., 2014; Vugrin et al., 2014; Zobel and Khansa, 2014; D'Lima and Medda, 2015; Soltani-Sobh et al., 2015; Ukkusuri, 2015; Alice and Behrouz, 2016; Soltani-Sobh et al., 2016a; Zhang and Wang, 2016; Chan and Schofer, 2016; Donovan and Work, 2017; El Rashidy and Grant-Muller, 2017; Thompson and Rajabifard, 2017; Liao et al., 2018; Aydin et al., 2018b; Xu et al., 2018; Leobons et al., 2019)
Adaptation	Adaptation is the capacity of the system to be flexible in responding to new pressures.	Characteristics of system: - Traffic flows; - Land users; - Population Size; - Number of transportation modes. Performance variables: - Travel Paths; - Capacity of the elements that make up the network; - Geographic location of the elements of the network; - Travel time; - Average delay;	(Murray-Tuite, 2006; Ta et al., 2009; Leu et al., 2010; Chen and Miller-Hooks, 2011; Vugrin et al., 2014; Nakanishi et al., 2014; Schweikert et al., 2015; Zhang and Miller-Hooks, 2015; Zhang et al., 2015; Nogal et al., 2016; Adjetey-Bahun et al., 2016a; Thompson and Rajabifard, 2017; Maria et al., 2017; Aydin et al., 2018a; Yazıcıoğlu et al., 2018; Engler et al., 2018; Liao et al., 2018; Lu, 2018)
Efficiency	Efficiency is the positive relationship of service provided by a static system with the service provided by a dynamic system. In transportation systems, the efficiency is the ability to support disruptions while maintaining a level of service and connectivity.	Characteristics of system: - Traffic flows; - Population density; Performance variables: - Number of elements that make up the network; - Capacity of the elements that make up the network; - Travel Paths;	(Reed et al., 2009; Ta et al., 2009; Ip and Wang, 2011; Omer et al., 2013; Jin et al., 2014; Vugrin et al., 2014; Zhang et al., 2015; Chopra et al., 2016; Zhang et al., 2017; Ganin et al., 2017; Aydin et al., 2018a; Ilbeigi, 2019)
Robustness	Robustness is the strength or capacity of elements, systems, and other units of analysis to support a certain level of stress or demand without suffering degradation or loss of function.	Characteristics of the system: - Traffic flows; - Number of network segments; - Number of transportation modes; - Population size; Performance variables: - Free flow traffic speed; - Volatility of traffic flow; - Travel time; - Frequency of risk; - Level of initial damage; - Speed of traffic closed to network capacity level;	(Murray-Tuite, 2006; Reed et al., 2009; Berche et al., 2009; Colicchia et al., 2010; Leu et al., 2010; Cox et al., 2011; Adams et al., 2012; Bocchini and Frangopol, 2012; Devanandham and Ramirez-Marquez, 2012; Tamvakis and Xenidis, 2012; Blockley et al., 2012; Omer et al., 2013; Osogami et al., 2013; Barker et al., 2013; Adjetey-Bahun et al., 2014; Bocchini et al., 2014; Bruyelle et al., 2014; Faturechi and Miller-Hooks, 2014; Nakanishi et al., 2014; Zobel and Khansa, 2014; D'Lima and Medda, 2015; Schweikert et al., 2015; Ukkusuri, 2015; Zhang and Miller-Hooks, 2015; Zhang et al., 2015; Baroud et al., 2015; Bhavathrathan and Patil, 2015; Alice and Behrouz, 2016; Duan et al., 2016; Adjetey-Bahun et al., 2016b; Kim and Yeo, 2016; Kim et al., 2016; Nogal et al., 2016; Soltani-Sobh et al., 2016a; Soltani-Sobh et al., 2016b; Zhang and Wang, 2016; Deloukas and Apostolopoulou, 2017; Donovan and Work, 2017; Maria et al., 2017; Rashidy and Grant-Muller, 2017; Wang et al., 2017; Calvert and Snelder, 2018; Lu, 2018; Aydin et al., 2018a; Aydin et al., 2018b; Tang and Heinimann, 2018; Yazıcıoğlu et al., 2018; Ilbeigi, 2019; Leobons et al., 2019; Markolf et al., 2019)
Interdependence	Interdependence represents the connection of the components of a system or its dimensions, including the network of relationships between the components of a system.	Characteristics of the system: - Number of intermodal stations; - Terminal lines; - Bus Lines; - Train lines; - Number of transportation modes; Performance variables: - Travel time;	(Ta et al., 2009; Leu et al., 2010; Jin et al., 2014; Rashidy and Grant-Muller, 2017)
Preparedness			

(*continued on next page*)

Table 2 (*continued*)

Characteristic	Description	Variables	Author(s)
	Preparation refers to "preparing certain measures prior to discontinuation," and enhancing the resilience of a system by reducing the effect of the potential negative impacts of disruptive events.	Characteristics of the system: - Traffic Flows; Performance variables: - Mitigation measures; - Average delay; - Associated costs; - Capacity of the elements that make up the network;	(Ivory and Trotter, 2020; Colicchia et al., 2010; Miller-Hooks et al., 2012; Osogami et al., 2013; Omer et al., 2013; Azadeh et al., 2014; Faturechi and Miller-Hooks, 2014; Zhang et al., 2015; Chan and Schofer, 2016; Deloukas and Apostolopoulou, 2017; Engler et al., 2018; Liao et al., 2018)
Flexibility	Flexibility is the capacity of a system to respond to shocks and adjust to changes through contingency planning after disruptions. It is also referred to as the ability to reconfigure resources to deal with uncertainties.	Characteristics of System: - Traffic flows; - Capacity of the network; Performance variables: - Alternative proximity infrastructures; - Average delay; - Average speed reduction; - Travel distance;	(Ta et al., 2009; Cox et al., 2011; Ip and Wang, 2011; Ishfaq, 2012; Barker et al., 2013; Azadeh et al., 2014; Soltani-Sobh et al., 2015; D'Lima and Medda, 2015; Alice and Behrouz, 2016; Soltani-Sobh et al., 2016a; Chan and Schofer, 2016; Aydin et al., 2018a; Tang and Heinimann, 2018; Markolf et al., 2019; Ilbeigi, 2019)
Rapidity	Rapidity is the capacity to meet priorities and achieve goals in a timely manner to contain losses and avoid future disruptions.	Characteristics of System: - Traffic flows; Performance variables: - Response time; - Speed of traffic recovery; - Capacity of the elements that make up the network.	(Adams et al., 2012; Bocchini and Frangopol, 2012; Devanandham and Ramirez-Marquez, 2012; Adjetey-Bahun et al., 2014; Zobel and Khansa, 2014; Faturechi and Miller-Hooks, 2014; Ukkusuri, 2015; Zhang and Wang, 2016; Alice and Behrouz, 2016; Zhang et al., 2017; Deloukas and Apostolopoulou, 2017; Leobons et al., 2019; Markolf et al., 2019)

concepts are applied transversally to all areas of transportation.

Characteristics such as efficiency, interdependence and preparedness are still not sufficiently explored when evaluating the resilience of transportation systems. Efficiency is applied across different dimensions of transportation systems and more specifically in freight transportation (Ta et al., 2009), railway transportation (Ip and Wang, 2011; Jin et al., 2014) and road transportation (Omer et al., 2013; Ganin et al., 2017; Aydin et al., 2018a; Ilbeigi, 2019). On the other hand, interdependence is mainly applied in studies about connectivity between different modes of transportation (Jin et al., 2014), in railways (Leu et al., 2010), in roads (Rashidy and Grant-Muller, 2017) and in freight transportation systems (Ta et al., 2009). Finally, preparedness is transversally associated with almost all transportation infrastructures (Zhang et al., 2015): freight transportation systems (Ivory and Trotter, 2020; Colicchia et al., 2010; Miller-Hooks et al., 2012; Azadeh et al., 2014), road transportation systems (Omer et al., 2013; Osogami et al., 2013; Faturechi and Miller-Hooks, 2014), railway transportation systems (Chan and Schofer, 2016; Deloukas and Apostolopoulou, 2017) and more broadly in the entire urban transportation system (Engler et al., 2018).

According to the analysis of works and definitions on the resilience of transportation systems, it was concluded that efficiency and flexibility characteristics are intrinsically related to other resilience characteristics. On the other hand, the interdependency is strongly related to connectivity and dependency characteristics of the performance of a transportation system. A transportation system can always be seen as an interconnected system of other transportation subsystems, especially in a multimodal urban context. Thus, interdependency should not be considered a main characteristic of resilience.

Following the same rationale, efficiency and robustness have similar definitions, since according to literature an efficient system has the ability to keep a good level of service and connectivity during disruption and a robust system has the ability to support a certain level of stress or demand without suffering degradation or loss of function. However, efficiency should be used to measure the performance of a transportation system and for that reason must not be considered as a main characteristic of resilience. Furthermore, we can consider that efficiency is already accomplished in the evaluation of robustness.

Another important issue is the relation among the very similar concepts of redundancy and flexibility in the resilience of transportation systems since both concepts refer to an "extra" capacity beyond the usual components for a transportation system respond to a disruption. However, redundancy is the oldest and most used in studies of the resilience of transportation systems. Thus, we argue that resilience studies should only use the term redundancy instead of flexibility.

Therefore, we can conclude that there are five main characteristics of the resilience of transportation systems: i) redundancy, ii) adaptation, iii) robustness, iv) preparedness, and v) rapidity.

As previously referred, the definition of the resilience of transportation systems consist in four main actions: i) resist, ii) recover, iii) absorb, and iv) transform, which is supported by the proposed five characteristics of the resilience of transportation systems. Fig. 1 presents the relation between the main characteristics and main actions of the resilience of a transportation system, based on the following rationale:

- If a system is robust and prepared, then it can resist most of the disturbances;
- If a system is robust, prepared and with recovering capacity within an acceptable time, then it can recover more easily and rapidly to the disturbances;
- if a system is redundant in relation to its subsystems, then it can absorb most of the disturbances and impacts;
- If a system cannot recover to the initial stage of operation, then it can adapt and transform to a different stage of equilibrium and operation.

In the literature it is possible to find a wide range of studies that integrate several variables (Table 2) used to assess the characteristics of the resilience of transportation systems, however, these are more related to the characterization and functioning of transportation systems than to the characteristics of resilience as can be seen in other review works (e.g. (Faturechi and Miller-Hooks, 2015; Zhou et al., 2019)). For this reason, a set of seven resilience indicators is proposed to make a

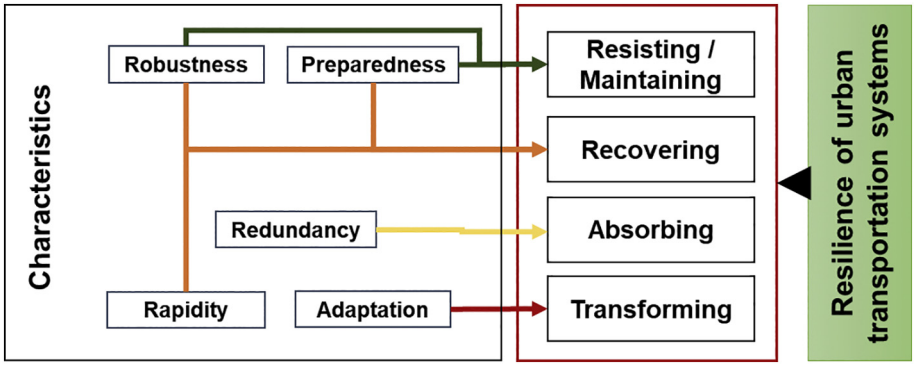

Fig. 1. The relation between the main characteristics and main actions of the resilience of a transportation system. (Source: own work).

Table 3
- Main proposal resilience indicators – variables of performance assessment of the resilience.

Variables used in resilience studies	Resilience indicators – variables of performance assessment of the resilience
- Travel distance - Travel time - Travel Paths - Traffic flow/ Traffic volumes - Geographic location of the elements of the network	- Multiple routes (travel characteristics - origin – destination)
- Capacity of the elements that make up the network - Bus lines - Train lines - Terminal lines - Number of intermodal stations - Number of the elements that make up the network - Network size - Alternative proximity infrastructures	- Extra infrastructure (links/ nodes) capacity
- Number of transportation modes - Walking and cycling flows - Traffic flows	- Diversity in transportation modes (ground vs. underground, walking/biking vs. motorized transportation, etc.)
- Land users - Population size - Population density	- Population data historic/ variation (number of inhabitants, population density, etc.)
- Level of initial damage - Volatility of traffic flow - Free flow traffic speed - Average speed - Speed of traffic with the network load	- Critical traffic data (flow, capacity and speed, etc.)
- Frequency of risk - Average speed reduction - Speed traffic recovery - Response time - Mitigations measures - Associated costs	- System performance to disruptions

better assignment with resilience characteristics, that in some extent can be seen as an aggregation of the existing transportation variables (Table 2). In Table 3 is presented a match between these two types of variables/ indicators.

The resilience indicators result from the aggregation of the set of variables used to characterize the system and the performance assessment most used in studies of the resilience of a transport system. In this work, we only intend to present a set of indicators that integrate the information of the variables that are usually used in resilience studies, but that, in addition, is more oriented to define and characterize the main characteristics of resilience. Thus, Table 4 presents the relationship/contribution that these indicators can make to assess the five main characteristics of the resilience of a transport system.

According to Table 4, it is possible to observe that the proposed indicators are transversal to several characteristics, i.e., an indicator can be used to define several characteristics. In fact, it is possible to foresee that the most used indicators to assess the resilience are multiple routes (travel characteristics - origin – destination), extra infrastructure (links/ nodes) capacity and diversity in transportation modes.

In summary, it is possible to conclude that there is room to explore and improve the definition and description of the resilience characteristics of the transportation system, namely in the definition/ selection of other/ new indicators and in the creation of an assessment methodology of the resilience of transportation system, which allows to identify, in a clear way, what is the contribution of the resilience solutions to solve the problems of a potential disruption event in relation to each of the five main characteristics of resilience.

5. Are the vulnerability and reliability characteristics of Transportation Resilience?

The number of studies about resilience in transportation systems is growing. There are several terms used to describe resilience, related concepts and its characteristics in transportation systems. However, some concepts are related to resilience from different perspectives. An example is a relation between resilience, vulnerability and reliability. Therefore, a brief analysis and discussion on the relationship between these three concepts are presented.

The concepts of vulnerability, reliability and resilience are often associated with assessing the performance of a transportation system (Faturechi and Miller-Hooks, 2015). Research on resilience, vulnerability and reliability is a well-established field today, with many published works (Iida, 1999; D'Este and Taylor, 2003; Taylor et al., 2006; Szeto, 2011; Mattsson and Jenelius, 2015; Reggiani et al., 2015; Wan et al., 2017). At a more conceptual level, there is still no consensus regarding definitions of terms of vulnerability and resilience. These two concepts are often related to the concept of reliability (Mattsson and Jenelius, 2015; Reggiani et al., 2015). Therefore, it is important to understand the relation and overlap between these three concepts.

5.1. Vulnerability and reliability concepts

The literature on the vulnerability of transportation systems has grown rapidly over the last decades (Mattsson and Jenelius, 2015). This concept presents various definitions and contexts. According to Berdica (2002), a vulnerable system is susceptible to extreme tensions. Khademi et al. (2015) state that vulnerability in the road transport system is susceptibility to incidents that can reduce considerably the road network serviceability. Yet, for Baroud et al. (2014a, 2014b) vulnerability is the ability of a disruptive event to adversely impact system performance. Colicchia et al. (2010) stated that supply chain vulnerability is defined as the existence of random disturbances that lead to deviations in the supply chain from normal, expected or planned activities that

Table 4
Relation between the proposal resilience indicators and the main characteristics of the resilience of transportation systems.

Proposal resilience indicators	Main characteristics				
	Redundancy	Adaptation	Robustness	Preparedness	Rapidity
Multiple routes (travel characteristics - origin – destination)	X	X	X	X	X
Extra infrastructure (links/ nodes) capacity	X	X	X	X	X
Diversity in transportation modes	X	X	X	X	X
Population data historic/ variation	X	X	X		
Critical traffic data		X	X	X	
System performance to disruptions			X	X	X

cause negative effects or consequences. According to Nicholson (2007), vulnerability refers to the facility with which the system can be pushed out of its state of stability or equilibrium. Finally, according to Knoop et al. (2012), vulnerability describes the weakness of a network. In summary, the vulnerability in transportation systems can be assumed as the susceptibility of systems to extreme tensions (incidents, disturbances, disruptions, etc.) with a reduction in its service level.

There are some definitions of reliability applied to transportation systems. A network is considered reliable if the expected trip costs are acceptable, even when users are extremely pessimistic about the state of the network (Bell, 2000). According to Berdica (2002), reliability describes the operability of the networks under varying strenuous conditions. According to Faturechi and Miller-Hooks (2014), system reliability is the probability of continued functionality post-event. Reza and Elise (2015) defined reliability as the probability that a network has to remain operative (often a function of connectivity) given the occurrence of a disaster or disruption event. However, reliability can be defined as the probability that the transportation network achieved as an acceptable level of service due to an unusual event (Soltani-Sobh et al., 2015). Finally, a reliable system performs its required functions under specified conditions for a specific period of time (Torrisi et al., 2017). Thus, reliability in transportation systems is when a system has acceptable operability (level of service) and acceptable trip costs during an extreme event (disturbance, disruption, interruption). On the other hand, transport networks are subject to variations in the demand and supply that may affect reliability (Nicholson et al., 2003; Szeto, 2011). Network reliability research has tended to focus on congested urban road networks and on the probability that a network delivers a required performance standard (Bell, 2000; Shlayan et al., 2011; Taylor, 2012; Mirjafari and Poorzahedy, 2018; Uchida, 2018).

5.2. Resilience and Vulnerability concepts

Resilience and vulnerability are closely related concepts that have attracted wide interest in the literature on transportation (Seeliger and Turok, 2013). There are several studies that relate resilience and vulnerability concepts applied to transportation systems. Berche et al. (2009) carried out an analysis of the effects that the removed nodes have on the functioning of the public transport networks, simulating different attack strategies based on vulnerability criteria. Mansouri et al. (2009) developed a Risk Management-based Decision Analysis (RMDA) framework to define the nature of resilience in Maritime Infrastructure Transport Systems (MITS). The framework was based on risk analysis and management methodologies, which helps to determine the nature of the uncertainty in the system, and consequently leads to devising strategies of resilience with respect to the known vulnerabilities of the system. Cox et al. (2011) presented operational metrics to determine the resilience of passenger transport systems against terrorism, presenting a set of proposed measures of prospective resilience to assess the potential resilience of a transportation system based on the vulnerability, flexibility, and availability of resources. Ip and Wang (2011) proposed a model to optimize the structure of transport networks, based on evaluating resilience and friability (reduction in the resilience of network caused by the removal of nodes or edges). Omer et al. (2012) proposed various schemes to improve resilience, reducing the vulnerability of the system and increasing its adaptability. The impact of the schemes on system resilience metrics is assessed by adopting the methodology of the Network Infrastructure Resilience Assessment (NIRA) framework. Blockley et al. (2012) applied a generalized vulnerability theory to an urban transportation network to assess the resilience of the system. Reggiani (2013) proposed a conceptual framework that aims to integrate the concept of the resilience of network in transport safety, examining the relevance of resilience to fragility (vulnerability). Baroud et al. (2014a, 2014b) presented and validated importance measures based on resilience to study important links of waterway networks, addressing the ability to quantify the vulnerability and capacity to recover inland waterways. Alice and Behrouz (2016) investigated resilience assessment and risk analysis as interconnected concepts, integrating vulnerability into the assessment of a system. Calvert and Snelder (2018) presented the Link Performance Index for Resilience (LPIR), which evaluates the level of resilience of individual road sections regarding the wider road network. LPIR can be used to detect poorly resilient road sections and analyse road and traffic characteristics that cause this non-resilience. The LIPR methodology added concepts to resilience such as robustness and vulnerability by also explicitly considering recovery from congestion events and by focusing on everyday operational traffic situations rather than just on disasters or major events. Finally, Lu (2018) proposed a resilience approach for a rail transit network under daily operational incidents, integrating the topological network (based on vulnerability analysis studies) and passenger volume characteristics. The vulnerability is an older and more established concept in transportation field than resilience (Reggiani et al., 2015).

The broader concept of vulnerability and the concept of resilience can, or may not, be opposites based on the characteristics of the system. Since a system may have a susceptibility to a disruption (poor robustness and poor capacity of absorption of the damages) and a good capacity of adaptation and redundancy to recovery part of initial characteristics. In this case, the system is vulnerable and resilient at the same time.

Nevertheless, the vulnerability can be treated in the same way as to risk. Furthermore, there are many variations in the definitions of risk, but most involve a combination of two parts: (1) the probability for an event of negative impact occurs, and (2) the extent of the consequences once this event has taken place (Berdica, 2002). Jenelius et al. (2006) argue that the concept of vulnerability should be divided into probability and consequence. However, Khademi et al. (2015) establish that risk is generally associated with something that entails negative consequences for the system. Following this, Taylor and D'Este (2007) and Maltinti et al. (2011) considered the definition of vulnerability should be related to the consequence rather than the probability of an event, since we can evaluate the consequences, impacts and exposure to define levels of criticality under previous scenarios of a potential disruption, which is considered as conditional stage. In this way, conditional consequences and conditional criticality of the transport system can be determined (Jenelius and Mattsson, 2012; Balijepalli and Oppong,

2014; Li et al., 2019). Thus, the concept of *conditional vulnerability* was introduced and can be seen as the aggregated consequences of a disruption (Mattsson and Jenelius, 2015).

The concept of *conditional vulnerability* is strongly related with the concept of Robustness (see Scott et al. (2006), De-Los-Santos et al. (2012), Cats and Jenelius (2015) and Rupi et al. (2015)). According to McDaniels et al. (2008), the occurrence of a disaster leads to a rapid decrease of the system performance. Yet, most of the time, some of the system operability is maintained, reflecting the robustness of the system to a given external shock. Over time, after the disaster, the system regains some level of stability or balance (mitigation and recovery actions).

Mattsson and Jenelius (2015) concluded that conditional vulnerability is the difference of performance between the initial level (baseline) and the level of the system after the disaster. With this, when any mitigation and recovery measures (preparedness) are not applied, the conditional vulnerability can be seen as a complementary stage of robustness, i.e., the conditional vulnerability is the damage suffered due to lack of robustness and preparedness. In consequence, conditional vulnerability is partly a main characteristic of resilience, since this is more related with the consequences caused by a disaster than with the probability for a disruption occurs (i.e. the negative risk associated with the exposure of a system before and/or during a disaster). Therefore, we concluded that conditional vulnerability can be seen as characteristic of the resilience of the transportation system. Even though conditional vulnerability is conversely associated with robustness, which is a more consistent and well-studied resilience characteristic. Thus, the conditional vulnerability could be estimated and evaluated through robustness and preparedness, and for that reason should be considered a main characteristic of resilience but not necessarily used due to its complementary effect to the other two characteristics.

5.3. Resilience and reliability concepts

According to the literature, resilience and reliability are also related concepts. In order to increase resilience, Soltani-Sobh et al. (2015) developed a model to quantify the improved reliability, which reduces recovery time after an uncertain disruption. This model provided accurate predictions of the system performance through three performance functions that estimate the total travel time flow and consumer surplus. Soltani-Sobh et al. (2016b) presented a model that incorporates reliability into classical facility location problems. This model arose from the recognition that the recovery of centres and ground transportation networks are vulnerable to disruptions of all sorts and that facility location decisions can be critical in reducing the impact of these disruptions. Kim et al. (2016) explored how potential failures on nodal disruptions affect transit system flows and examined the change in the reliability of transit systems. For the methodology, network reliability and system flow loss were used and the criticality of stations under a variety of simulated nodal disruptions was assessed. Network resilience was evaluated by identifying the best and worst geographical impact scenarios on networks. Finally, Zhang and Wang (2016) proposed a resilience-based framework for mitigating the risk of surface road transportation networks, by introducing a novel metric based on system reliability and network connectivity to measure the resilience-based performance of a road transportation network.

From the literature, we can conclude that reliability is very important to evaluate the resilience of a transportation system, since the more reliable the more resilient. However, reliability is not a main characteristic of resilience, but can also be seen as a transversal characteristic that is used to evaluate the performance of a transportation system facing or not a disruption event. Thus, it can be argued that reliability should not be considered a main characteristic of resilience.

5.4. Resilience, vulnerability and reliability

There are other works where performance measures can be found relating the concepts of resilience, vulnerability and reliability. When assessing resilience considering the interaction of four paradigms: reliability, vulnerability, survivability and recoverability, Barker et al. (2013) proposed a two-step method: (i) network component importance measures to identify the components that are most influential when considering the resilience of the entire network, and (ii) providing a discrimination algorithm to identify component importance. Baroud et al. (2014b) introduced stochastic metrics of network resilience that allow quantitative analysis under uncertainty of the time needed for a disrupted network to regain full operation after a disruptive event. This work defines network resilience throughout the dimensions of reliability, vulnerability, survivability, and recoverability, and quantifies network resilience as a function of component and network performance.

Thus, by analysing the literature relating the concepts of resilience, vulnerability and reliability, it can be concluded that these concepts are interrelated and complementary measures when assessing the performance of transportation systems in disruption context. Therefore, it is important to stress that reliability is related to the acceptable operability of the entire transportation system in different contexts including a disruption scenario, vulnerability is related to susceptibility to face a disruption and in that sense can be seen as trigger for resilience, but as conditional vulnerability can be considered as characteristic of resilience, and resilience that is mainly related with the system response to a disruption event, thus to the recoverability of a system.

6. Application areas of the resilience of urban transportation systems

According to the literature, resilience analyses of urban transportation systems are focused on post-disaster analysis, more specifically after the occurrence of natural disasters (Freckleton et al., 2012; Nakanishi et al., 2014; Zobel and Khansa, 2014; Chan and Schofer, 2016; Nogal et al., 2016), such as earthquakes (Shafieezadeh and Ivey Burden, 2014; Alice and Behrouz, 2016; Duan et al., 2016) and hurricanes (Reed et al., 2009).

Resilience of an urban transportation system mainly applies to: (i) transportation infrastructure, where the structural resilience of infrastructures is analysed; (ii) operation/use of the transportation system, where the functional performance of the systems and their risks are assessed against a disturbance (interruption, shock, perturbation, disaster). However, studies that incorporate and link the structural and functional aspects of the transportation system are still very limited.

In recent years, resilience has been applied in several specific areas of the urban transportation system, demonstrating the broadness and scope of this concept, covering rail and road systems separately or in an integrated manner as urban systems.

Currently, resilience analyses in the specific area of road transportation systems have attracted much attention, and the relationship between supply and demand (traffic flow) was the main analytical variable used to evaluate resilience (Murray-Tuite, 2006; Leu et al., 2010; Ishfaq, 2012; Lhomme et al., 2013; Chan and Schofer, 2016; Calvert and Snelder, 2018; Tang and Heinimann, 2018). This specific area (roads) of transportation is the most cited in the literature, in which twenty-two studies were found concerning this topic and sixteen of those were published over last five years (2015-2020) (Murray-Tuite, 2006; Bocchini and Frangopol, 2012; Omer et al., 2013; Osogami et al., 2013; Lhomme et al., 2013; Faturechi and Miller-Hooks, 2014; Bhavathrathan and Patil, 2015; Soltani-Sobh et al., 2015; Zhang et al., 2015; Nogal et al., 2016; Zhang and Wang, 2016; Kim and Yeo, 2016; Maria et al., 2017; El Rashidy and Grant-Muller, 2017; Thompson and Rajabifard, 2017; Zhang et al., 2017; Donovan and Work, 2017; Ganin et al., 2017; Aydin et al., 2018b; Tang and Heinimann, 2018; Calvert and Snelder,

Table 5
Main Methods and techniques adopted to measure and/or improve the resilience of transportation systems.

Characteristic	Methods/Techniques: Conceptual Framework	System Dynamics	Stochastic processes	Simulation	Optimisation processes	Monte Carlo Method	Fuzzy theory	Network science	Author(s)
Redundancy	■								(Ta et al., 2009; Cox et al., 2011; Tamvakis and Xenidis, 2012; Markolf et al., 2019)
		■							(Berche et al., 2009; Leu et al., 2010; Chen and Miller-Hooks, 2011; Adjetey-Bahun et al., 2014; Zobel and Khansa, 2014; Ukkusuri, 2015; Soltani-Sobh et al., 2015; Zhang and Wang, 2016; Chan and Schofer, 2016; Soltani-Sobh et al., 2016a; Rashidy and Grant-Muller, 2017; Tang and Heinimann, 2018; Ilbeigi, 2019; Leobons et al., 2019)
			■						(Ishfaq, 2012; Jenelius and Mattsson, 2012; Miller-Hooks et al., 2012; Barker, Ramirez-Marquez and Rocco, 2013; Osogami et al., 2013; Faturechi and Miller-Hooks, 2014; Jin et al., 2014; D'Lima and Medda, 2015; Alice and Behrouz, 2016; Zhang et al., 2017; Xu et al., 2018)
				■					(Leu et al., 2010; Lhomme et al., 2013; Osogami et al., 2013; Adjetey-Bahun et al., 2014; Azadeh et al., 2014; Alice and Behrouz, 2016; Donovan and Work, 2017; Liao et al., 2018; Ilbeigi, 2019)
					■				(Ip and Wang, 2011; Bocchini and Frangopol, 2012; Jenelius and Mattsson, 2012; Omer et al., 2013; Vugrin et al., 2014; Alice and Behrouz, 2016; Thompson and Rajabifard, 2017; Zhang et al., 2017; Liao et al., 2018; Xu et al., 2018)
						■			(Chen and Miller-Hooks, 2011; Miller-Hooks et al., 2012; Zhang and Wang, 2016; Aydin et al., 2018a)
							■		(Freckleton et al., 2012; Azadeh et al., 2014)
								■	(Ip and Wang, 2011; Adjetey-Bahun et al., 2014; Alice and Behrouz, 2016; Soltani-Sobh et al., 2016a; Aydin et al., 2018b)
Adaptation	■								(Ta, Goodchild and Pitera, 2009; Nakanishi et al., 2014)
		■							(Murray-Tuite, 2006; Leu et al., 2010; Nogal et al., 2016; Yazıcıoğlu et al., 2018)
			■						(Chen and Miller-Hooks, 2011; Zhang and Miller-Hooks, 2015; Zhang et al, 2015; Adjetey-Bahun et al., 2016a; Maria et al., 2017)
				■					(Leu et al., 2010; Schweikert et al., 2015; Aydin et al., 2018a; Liao et al., 2018)
					■				(Vugrin, Turnquist and Brown, 2014; Thompson and Rajabifard, 2017; Engler et al., 2018; Lu, 2018)
						■			(Chen and Miller-Hooks, 2011; Maria et al., 2017; Aydin et al., 2018a)
								■	(Murray-Tuite, 2006; Adjetey-Bahun et al., 2016a; Yazıcıoğlu et al., 2018)
Robustness	■								(Cox et al., 2011; Adams et al., 2012; Blockley et al., 2012; Tamvakis and Xenidis, 2012; Bruyelle et al., 2014; Nakanishi et al., 2014; Deloukas and Apostolopoulou, 2017; Markolf et al., 2019)
		■							(Murray-Tuite, 2006; Berche et al., 2009; Reed et al., 2009; Leu et al., 2010; Adjetey-Bahun et al., 2014; Zobel and Khansa, 2014; Ukkusuri, 2015; Soltani-Sobh et al., 2016a; Zhang and Wang, 2016; Kim and Yeo, 2016; Kim et al., 2016; Nogal et al., 2016; Rashidy and Grant-Muller, 2017; Ganin et al., 2017; Tang and Heinimann, 2018; Yazıcıoğlu et al., 2018; Ilbeigi, 2019; Leobons et al., 2019)
			■						(Barker et al., 2013; Osogami et al., 2013; Faturechi and Miller-Hooks, 2014; Baroud et al., 2015; D'Lima and Medda, 2015; Zhang and Miller-Hooks, 2015; Zhan et al., 2015; Duan et al., 2016; Zhang et al., 2017; Maria et al., 2017; Calvert and Snelder, 2018)
				■					(Le et al., 2010; Osogami et al., 2013; Adjetey-Bahun et al., 2014; Schweikert et al., 2015; Alice and Behrouz, 2016; Kim and Yeo, 2016; Kim et al., 2016; Donovan and Work, 2017; Ganin et al., 2017; Aydin et al., 2018a; Ilbeigi, 2019)
					■				(Bocchini and Frangopol, 2012; Devanandham and Ramirez-Marquez, 2012; Omer et al., 2013; Bocchini et al., 2014; Vugrin et al., 2014; Bhavathrathan and Patil, 2015; Alice and Behrouz, 2016; Zhang et al., 2017; Thompson and Rajabifard, 2017; Wang et al., 2017; Lu, 2018)
						■			(Colicchia et al., 2010; Zhang and Wang, 2016; Maria et al., 2017; Aydin et al., 2018a)
							■		(Freckleton et al., 2012)
								■	(Murray-Tuite, 2006; Adjetey-Bahun et al., 2014; Alice and Behrouz, 2016; Chopra et al., 2016; Adjetey-Bahun et al., 2016c; Soltani-Sobh et al., 2016a; Aydin et al., 2018b; Yazıcıoğlu et al., 2018)
Preparedness	■								(Ivory and Trotter, no date; Deloukas and Apostolopoulou, 2017)
		■							(Chan and Schofer, 2016)
			■						(Miller-Hooks et al., 2012; Osogami et al., 2013; Faturechi and Miller-Hooks, 2014; Zhang et al., 2015)
				■					(Osogami et al., 2013; Liao et al., 2018)
					■				(Miller-Hooks et al., 2012; Omer et al., 2013; Engler et al., 2018; Liao et al., 2018)
						■			(Colicchia et al., 2010)
							■		(Azadeh et al., 2014)
Rapidity	■								(Adams et al., 2012; Deloukas and Apostolopoulou, 2017; Markolf et al., 2019)
		■							(Adjetey-Bahun et al., 2014; Zobel and Khansa, 2014; Ukkusuri, 2015; Zhang and Wang, 2016; Leobons et al., 2019)
			■						(Faturechi and Miller-Hooks, 2014; Alice and Behrouz, 2016; Zhang et al., 2017)
				■					(Adjetey-Bahun et al., 2014; Alice and Behrouz, 2016)
					■				(Bocchini and Frangopol, 2012; Devanandham and Ramirez-Marquez, 2012; Zhang et al., 2017)
						■			(Zhang and Wang, 2016)
								■	(Adjetey-Bahun et al., 2014; Alice and Behrouz, 2016)

2018; Ilbeigi, 2019). Nevertheless, it was observed that the second most cited specific area was the railway transportation system (Leu et al., 2010; Ip and Wang, 2011; Adjetey-Bahun et al., 2014; Bruyelle et al., 2014; Jin et al., 2014; Bhavathrathan and Patil, 2015; Zhang and Miller-Hooks, 2015; D'Lima and Medda, 2015; Kim et al., 2016; Chan and Schofer, 2016; Chopra et al., 2016; Adjetey-Bahun et al., 2016a, 2016b; Deloukas and Apostolopoulou, 2017; Lu, 2018; Xu et al., 2018), in which sixteen studies were found on this topic. On the other hand, freight transportation systems have also attracted some attention but at a lower level compared to the other two areas (Ivory and Trotter, 2020; Colicchia et al., 2010; Chen and Miller-Hooks, 2011; Adams et al., 2012; Ishfaq, 2012; Miller-Hooks et al., 2012; Azadeh et al., 2014).

Finally, the resilience of transportation systems has also been studied on a wider scale, such as an urban system, integrating various surface transport systems such as roads and railways, and these studies are used mainly to assess: (i) the infrastructure resilience (Reed et al., 2009; Blockley et al., 2012; Vugrin et al., 2014; Zobel and Khansa, 2014; Baroud et al., 2015; Schweikert et al., 2015; Alice and Behrouz, 2016; Duan et al., 2016; Soltani-Sobh et al., 2016a; Aydin et al., 2018a) and (ii) the system resilience (Berche et al., 2009; Cox et al., 2011; Tamvakis and Xenidis, 2012; Freckleton et al., 2012; Barker et al., 2013; Bocchini et al., 2014; Nakanishi et al., 2014; Ukkusuri, 2015; Zhang et al., 2015; Wang et al., 2017; Yazıcıoğlu et al., 2018; Engler et al., 2018; Liao et al., 2018; Leobons et al., 2019; Markolf et al., 2019).

7. Methods adopted to measure and/or to improve the resilience of urban transportation systems

Identifying methods to measure and/or to improve the resilience of a transportation system is one of the main challenges and, at the same time, an enigma due to a large number of methods and techniques that have been used for this purpose, ranging from mathematical models to conceptual frameworks, which are described as follows:

- Conceptual framework: a matrix of concepts that is the basis of a coherent structure for the accomplishment of any task (Guimarães, 2007), and for the organisation of concepts and tasks and phases of execution. This technique is mainly used to initially define a problem and methodology, and other techniques to quantify the results (Ta et al., 2009).
- System Dynamics: a methodological approach to understanding the behaviour of complex systems over time (Abdel-Hamid and Madnick, 1991). This technique is mainly used in transportation

systems to assess traffic flow disturbances (Murray-Tuite, 2006) and infrastructures (Omer et al., 2012).

- Stochastic processes: this corresponds to a family of random variables that represent the evolution of a system of values over time (Allen, 2010). This technique is mainly used to characterize the behaviour of the transportation system (Reed et al., 2009; Baroud et al., 2014a; Jin et al., 2014; D'Lima and Medda, 2015).
- Simulation: is used to study the performance of a system under different scenarios, through a calibration and validation process (Rodrigues, 2014). It is a very useful tool to describe and predict system behaviour to evaluate the resilience of a transportation system in relation to hypothetical consequences of different testing scenarios (Lhomme et al., 2013; Nakanishi et al., 2014; Kim and Yeo, 2016; Ganin et al., 2017).
- Optimization processes: processes to find the best solution among all feasible solutions according to a certain objective function. The optimization problem can be divided into two categories depending on whether the variables are continuous or discrete (Hromkovič, 2013). This technique is mainly used to measure the impact of disruptions on the performance of transportation networks (Ip and Wang, 2011; Omer et al., 2013).
- Monte Carlo Method: a statistical methodology that is based on a large number of random samples to approximate the actual results (Hromkovič, 2013). It is a technique that is used to assess the performance of transportation systems through hypothetical scenarios and validation of methodologies (Colicchia et al., 2010; Miller-Hooks et al., 2012; Maria et al., 2017).
- Fuzzy theory: a form of multivariate logic in which the logical values of the variables can be any real number between 0 (FALSE) and 1 (TRUE). Fuzzy logic has been extended to deal with the concept of the partial truth, where the truth value can comprehend between completely true and false (Ahlawat et al., 2014). It is mainly used for evaluating hypothetically resilient scenarios (Freckleton et al., 2012; Azadeh et al., 2014).
- Network Science: is a network approach that uses the representation of physical, biological, and social phenomena to define predictive models (Barabási, 2013; Perera et al., 2017; Bioglio et al., 2019). Graph theory is a specific method of the network science that was recently used in several works (Murray-Tuite, 2006; Adjetey-Bahun et al., 2014; Adjetey-Bahun et al., 2016a; Zhang and Wang, 2016).

Table 5 shows the most used methods to measure and/or to evaluate the improvement of resilience according to the five main resilience characteristics identified in Table 2. Almost all the methods are used to measure and assess the main resilience characteristics. Thus, there is not a specific tool to measure each characteristic of resilience, since some tools can be used to measure several characteristics.

In Table 5 are identified the main works found in the literature related to defining each of the five main resilience characteristics, being possible to define the following metrics:

- systems dynamics models, stochastic processes, optimization processes, simulation method and conceptual framework are analysed in twenty-two, nineteen, seventeen, fifteen and ten studies, respectively.
- Monte Carlo method (not evaluating preparedness) and network science approach (not evaluating the preparedness) with seven and ten works, respectively.
- the fuzzy theory was the least used method with only two works founded to evaluate only three characteristics (redundancy, robustness, and preparedness).

It is important to note that stochastic analyses are sometimes associated with Monte Carlo method to validate specific methodologies. Two studies can be highlighted in the literature: (i) Miller-Hooks et al. (2012) that studied the maximization of resilience in freight transportation networks with limited economic resources and service levels, using the formulation of a two-step stochastic program through Monte Carlo method; and, (ii) Chen and Miller-Hooks (2011) that defined an indicator of network resilience, which quantifies the ability of an intermodal freight transport network to recover from disruptions due to natural or human-caused disasters. For this a stochastic mixed-integer program for quantifying network resilience and identifying an optimal post-event course of action (i.e., set of activities) to take. To solve this, a mathematical program that accounts for dependencies in the random link attributes based on Benders decomposition, column generation, and Monte Carlo method concepts were proposed.

It is also important to highlight that simulation was mainly used to measure and analyse the resilience performance in (i) of transportation systems (Leu et al., 2010; Osogami et al., 2013; Lhomme et al., 2013; Adjetey-Bahun et al., 2014; Azadeh et al., 2014; Kim and Yeo, 2016; Kim et al., 2016; Donovan and Work, 2017; Ganin et al., 2017; Liao et al., 2018; Ilbeigi, 2019), and (ii) transportation infrastructures (Schweikert et al., 2015; Alice and Behrouz, 2016; Aydin et al., 2018a).

Moreover, there are other studies about the resilience of transportation systems with some interest despite not being used so frequently. Murray-Tuite (2006) studied the influence of optimal traffic evaluations and road network equilibrium, based on two resilience characteristics (adaptability and robustness), using system dynamics models. Berche et al. (2009) carried out an analysis of the effects that the removal of nodes have on the functioning of public transport networks, using system dynamics models, and simulating different strategies of directed attack derived from vulnerability criteria, which resulted in minimal strategies to reduce the impacts in those systems. Ip and Wang (2011) introduced the concept of "friability" (reduction of network resilience caused by the removal of nodes or links in railways) using an optimization model. Jin et al. (2014) studied the integration between public buses with the metro system, developing a two-step stochastic program formulation to improve the resilience of metro networks by leveraging public bus services. More recently, Alice and Behrouz (2016) provided a comprehensive computational framework to include several sources of uncertainty that must be taken into account to estimate the level of seismic risk in order to assess the seismic resilience of highway bridge networks exposed to deterioration processes. In this framework, the authors provided a more realistic estimation of the post-event functionality of transportation networks.

As in all evaluation processes, models of measuring and/or improving resilience can also present a qualitative or quantitative character, which includes conceptual structures, simulation models and mathematical models. Thus, in most of the literature, resilience is determined using complex mathematical models of theoretical nature, but that is very difficult to apply in practical approaches. Consequently, it was sometimes not sufficient to describe resilience by adopting only mathematical equations, especially in real situations. Therefore, the difficulty to comprehend and put in practice resilience assessment by transportation authorities and related entities may inevitably result in a disinterest in the development of integrated and complex models to measure and assess the improvement in resilience (Wan et al., 2017). Thus, studies are still scarce based on models and decision support tools with a level of practical applicability that can be considered easy and friendly to use and understand.

In short, analysing the resilience of urban transportation systems, incorporating infrastructures, network operation and simulation methods can lead to developing and constructing user-friendly and practical/technical tools, which represents a future line of research in the field of resilience. The use of simulation tools would allow a predictive analysis of resilience for all transportation systems, identifying the most affected components, alerting the entities to intervene in critical zones and other analysis considered important by public authorities.

Finally, Fig. 2 presents the interconnection between the various concepts, definitions, characteristics and methods adopted to measure

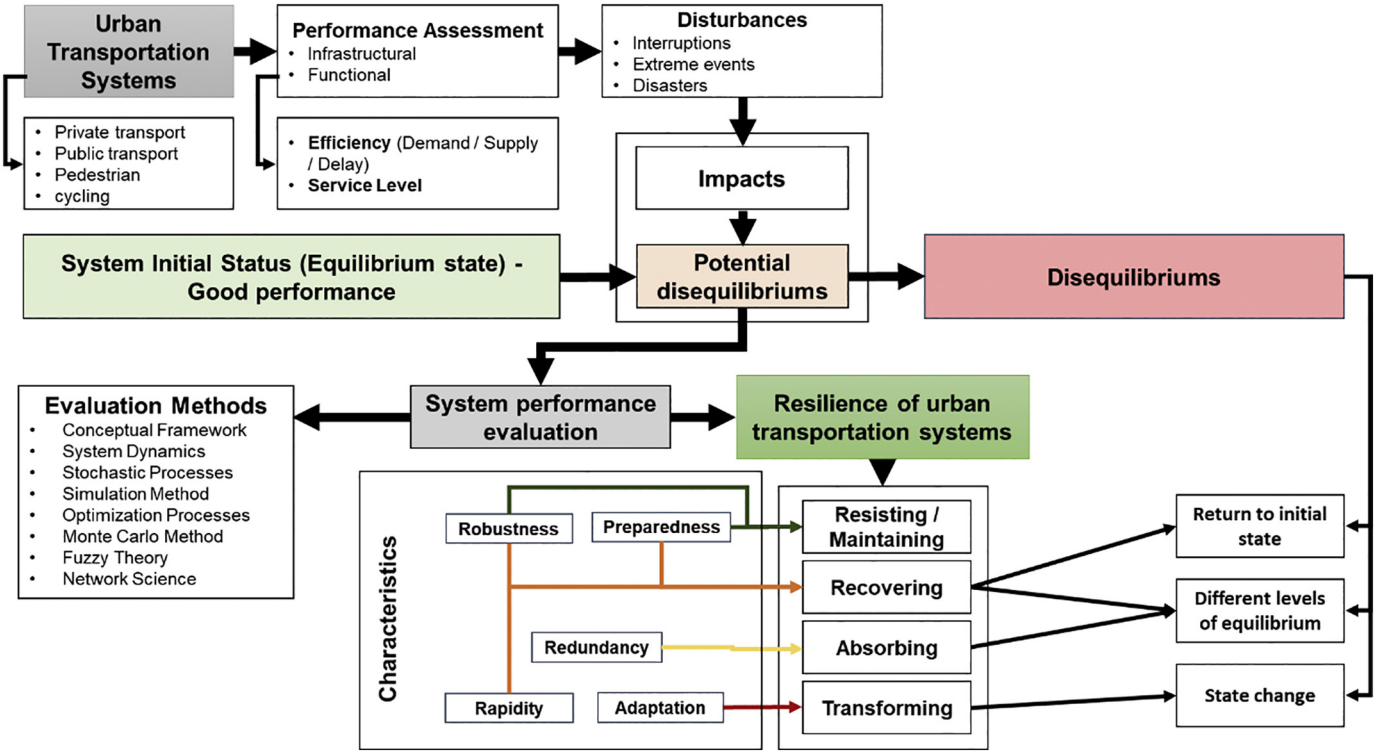

Fig. 2. The relation between the various concepts of the resilience of urban transportation systems (source: own work).

and/or improve resilience, which must be a support structure of a process for developing new methodologies for evaluating the resilience, i.e. the operability and use, of the transportation systems against potential disturbances.

8. Strengths, weaknesses and potential trends for future research in the resilience of transportation systems

Among other issues, this work addressed the main issues associated with the definition of transport system resilience, how resilience can be described and assessed through the identification of its main characteristics and the main assessment methods used in various works in this field. Therefore, it is important to present the main strengths and weaknesses of the main studies on the resilience of the transport system (Table 6).

Thus, based on the identification of the main weaknesses and strengths of the main works on this subject (Table 6), as well as some proposals from various authors that are often associated with the specific context of the research in question, a set of potential research trends on resilience of transportation system are presented, as follows:

- The methodologies must be developed to be adapted and applied to all transport systems;
- The integration of behaviour/ mobility models to provide additional insights into the resilience process;
- The addition of new resilience variables and indicators

Table 6
Main strengths, weaknesses and future researches on the Resilience of transportation systems.

Main strengths	Main weaknesses
- The resilience approaches can illustrate the complexity of a compound disaster event; - Resilience is becoming a well-studied issue, supported by full approaches that comprehend all phase of a disruption event (before, during and after) The Resilience concept is supported in five main known characteristics (Robustness, …; - Large number and diversity of methods and technics to evaluate the resilience of transportation systems; - Analysis of the resilience for the components (links and nodes) and the entire network of the transportation systems allow to study and define more suitable preparedness and mitigation measures and reduce vulnerability; - An optimization approach can identify the optimal recovery responses for disrupted transportation networks, which can provide tools for the decision-makers and the authorities to define more suitable strategies;	- It can be difficult to predict how a system might be damaged due to the uncertainty of the nature of disasters, and can only be considered a finite number of possible locations for the event; - Several characteristics of resilience that are complementary to each other, and sometimes related but not integrated characteristics of resilience. - A mix of conventional system and performance variables with resilience variables of a transportation system; - The traffic assignment methodology should not be the only factor in assessing transportation resilience; - The travel times on links outside the disrupted areas cannot be affected by the change in traffic flows due to the event; - The size and complexity of systems can become impossible to quantify and compare resilient solutions and can increase the computational time; - The specific results of a sample network cannot be generalized to any transportation system; - The social and organizational resilience must be assessed as well to ensure a more holistic approach necessary to improve resilience. - The complexity of the methods used to evaluate resilience can be considered a barrier for potential usage by others; - lack of historic consequences for disruption events that accomplish past and post-event features.

(probabilistic behaviour, cost-evaluation, etc.) to the developed models;

- To explore and improve the description of the resilience characteristics of the transportation system, namely in the selection of new resilience indicators;
- To explore and create an assessment methodology of the resilience of transportation system that allows to identify what is the contribution of the resilience solutions in relation to each of the five main characteristics of resilience;
- The incorporation of alternative measures and experiments to investigate additional properties of transportation networks (topological properties);
- To define calibration and validation processes to assess the impact on disruption events on the physical network of transportation systems;
- The integration of system redesign in optimization approaches with recovery responses to improve resilience;
- The evaluation of the impact of implementing resilience enhancement strategies;
- The development of models integrating both pre-disruption preparedness and post-disruption recovery actions;
- To assess (either qualitatively or quantitatively) the effectiveness of Redundancy, Adaptation, Robustness, Preparedness, and Rapidity in order to help decision-makers determine the most appropriate course of action;
- A sensitivity analysis to determine the prioritization of improvement projects giving specific attention to attributes that carry more weight;
- The development of the resilience models focused on the optimal allocation of resources;
- To transform the idea of moving beyond robustness (toward resilience) from the abstract to the implementable;

9. Conclusion

Due to greater exposure to extreme events of a natural and human nature, there has been an increased concern in society with the capacity of urban systems to resist and ensure security, safety and quality of life during the occurrence of disturbances, in particular in the transportation system. Thus, technicians, politicians and scientists have paid greater attention to promote the resilience of urban transportation systems.

In this context, this article aimed to deconstruct the concept, analyse the dimensions and identify the main characteristics of the resilience of an urban transportation system, having presented a general and comprehensive framework to support a future model for evaluating urban transportation system resilience that would allow to provide a set of basic knowledge frameworks for technical staff, policymakers and the scientific community in general.

According to literature, different perspectives and approaches are reflected in the existing definitions of the resilience of the transportation systems. Thus, from the study of the concepts and definitions, characteristics, and areas of applicability, it can be concluded that the resilience of an urban transportation system is the ability of a system to resist, reduce and absorb the impacts of a disturbance, maintaining an acceptable level of service (static resilience), and restoring the regular and balanced operation within a reasonable period of time and cost (dynamic resilience).

From the main works on the resilience of an urban transportation system, there are mainly eight characteristics to assess the resilience of transportation systems, such as redundancy, adaptation, efficiency, robustness, interdependence, preparedness, flexibility and rapidity. However, some characteristics are more related with the operability of the transportation system, such as interdependence, efficiency and flexibility, and in addition, some have a high level of overlap with other characteristics more used and consolidated in studies on resilience, such as, robustness with efficiency and redundancy with flexibility, which may consequently not be considered as main characteristics of resilience of transportation systems. Thus, it can be concluded that the main characteristics of the resilience of transportation systems are: redundancy, adaptation, robustness, preparedness and rapidity.

The resilience of a transportation system can be assessed in terms of its infrastructure/ network and/or its level of operation and usage. However, it could be observed that there is a very limited number of studies on resilience that simultaneously incorporate both the infrastructure and the operation of the transportation system. This research mainly included research on urban transportation systems (railway, road and freight). It should also be noted that the most commonly cited transportation area in resilience studies is related to freight systems.

Currently, the analysis of the resilience of transportation systems, mainly roads, is evaluated similarly to the analysis of performance conventionally used in current mobility studies, i.e., focusing on the measurement of variables related to the mismatches between supply and demand, such as delays, travel speed, traffic flows vs capacity, among others. In addition, from the analysed works, it was proposed several resilience indicators that are related to the five main characteristics of resilience, such as, multiple routes (travel characteristics - origin – destination), extra infrastructure (links/ nodes) capacity, diversity in transportation modes, population data historic/ variation, critical traffic data and system performance to disruptions.

In literature, there are eight methods and techniques that are used to measure and/or improve the resilience of transportation systems, such as, conceptual frameworks, systems dynamics, stochastic processes, simulation method, optimization processes, Monte Carlo method, fuzzy and network science. On the other hand, the most used methods in quantitative evaluations are the systems dynamics models, stochastic and optimization processes, while qualitative evaluations are usually based on conceptual frameworks. Resilience is assessed based on complex mathematical models, which enhances the difficulty in understanding and putting into practice the developed methodologies. In addition, analysing the resilience of urban transportation systems, incorporating infrastructures, network operation and simulation methods can lead to developing and constructing user-friendly and practical/technical tools, which represents a future line of research in the field of resilience.

From the analysis of the main weaknesses and strengths, and by the future trends identified in some of the main works on the resilience of transportation systems it is possible to highlight the following future research trends in this domain:

- integrate behaviour/ mobility models to provide additional insights into the resilience process;

- explore and improve the knowledge about the resilience characteristics of the transportation system, namely in the selection of indicators of resilience;

- create an assessment methodology of the resilience of the transportation system stratified by the five main characteristics of resilience;

- evaluate the impact of implementing resilience enhancement strategies in new evaluation methodologies;

- develop models integrating both pre-disruption preparedness and post-disruption recovery actions;

- develop a sensitivity analysis to determine the prioritization of improvement projects giving specific attention to attributes that carry more weight.

Finally, this work will provide a potential guide to construct, or extend, the concept of resilience to the specific context of urban mobility.

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