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Zhuyu Yang, Bruno Barroca, Aurélia Bony-Dandrieux, Hélène Dolidon. Resilience Indicator of Urban Transport Infrastructure: A Review on Current Approaches. *Infrastructures*, 2022, 7 (3), pp.33. 10.3390/infrastructures7030033 . hal-03601121

**HAL Id: hal-03601121**

**<https://imt-mines-ales.hal.science/hal-03601121>**

Submitted on 8 Mar 2022

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Review

# Resilience Indicator of Urban Transport Infrastructure: A Review on Current Approaches

Zhuyu Yang<sup>1,2,\*</sup>, Bruno Barroca<sup>1</sup>, Aurélie Bony-Dandrieux<sup>3</sup> and Hélène Dolidon<sup>4</sup><sup>1</sup> Lab'Urba, Université Gustave Eiffel, 77420 Champs-sur-Marne, France; bruno.barroca@univ-eiffel.fr<sup>2</sup> LATTs, Université Gustave Eiffel, 77420 Champs-sur-Marne, France<sup>3</sup> Laboratoire des Sciences des Risques (LSR), IMT Mines Ales, 30100 Ales, France; aurelia.bony-dandrieux@mines-ales.fr<sup>4</sup> Cerema Ouest, 44000 Nantes, France; helene.dolidon@cerema.fr

\* Correspondence: zhuyu.yang@univ-eiffel.fr

**Abstract:** Urban transport infrastructures (TIs) play a central role in an urban society that faces more and more disasters. TIs, part of critical infrastructures (CIs), are highly correlated with urban disaster management in terms of their resilience when cities are facing a crisis or disaster. According to many studies, indicator assessment has been frequently used for the resilience management of CIs in recent decades. Defining and characterizing indicators can be useful for disaster managers as it could help monitor and improve the capacities and performance of TIs. The purpose of this paper, therefore, is (1) to identify and summarize the existing indicators of TIs resilience from the currently available literature, and (2) to discuss the possible future studies of the resilience indicator of TIs. The first results indicated that there are some barriers to identify indicators following the common search method through keywords. Additionally, the indicators found are mainly related to technical information, the disruption stage, and internal TIs. Finally, due to the complexity of indicator assessment, sub-indicators and indicator spatialization are widely used in the resilience assessment of urban TIs studies.



**Citation:** Yang, Z.; Barroca, B.; Bony-Dandrieux, A.; Dolidon, H. Resilience Indicator of Urban Transport Infrastructure: A Review on Current Approaches. *Infrastructures* **2022**, *7*, 33. <https://doi.org/10.3390/infrastructures7030033>

Academic Editor: Davide Forcellini

Received: 14 January 2022

Accepted: 1 March 2022

Published: 3 March 2022

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**Keywords:** resilience assessment; assessment indicator; transport network; critical infrastructure

## 1. Introduction

According to a recent report of the United Nations, 55% of the world's population lives in urban areas, a proportion that is expected to increase to 68% by 2050 [1]. Therefore, cities will remain the main place for global human development in the future. Recently, "resilience" is a constantly discussed topic for a broad range of academic approaches, such as environmental studies, civil engineering, and socio-political science. The popularity of "resilience" makes also resilient cities become an increasingly favored concept, especially concerning the challenge of human and natural disasters [2]. In urban systems, critical infrastructures (CIs), such as buildings, transportation networks, and energy and water grids, represent principal components due to their indispensable role in the maintenance of critical societal functions. The urban defense and economic activities could be weakened due to the potential destruction of critical infrastructures (CIs) [3]. In this context, the change and improvement of urban CIs have an opportunity to make cities more resilient.

Considered as an important part of the CIs system, the urban transport infrastructures (TIs) support a wide variety of activities ranging in modern societies and play a critical role in economic competitiveness and quality of life [2–6]. Urban streets, roads, and railways are components of the urban track infrastructure, which belong to the category of spatial networks, contrary to non-spatial networks such as the internet, social networks, and biological systems (e.g., human blood transport system) [7,8]. However, urban transport networks are vulnerable to congestion, accidents, weather conditions, special events, and

natural disasters. In Genoa, Italy, a city of some 580,000 inhabitants and the first Mediterranean port, a 200-m section of the Morandi Bridge collapsed on 14 August 2018, including one of its three supporting towers. This tragedy had wide echoes in the international press since it killed 43 people, left 600 homeless, and caused an economic disaster for Genoa [9]. In the short term, it created chaotic traffic in the city center, even congestion traffic around the urban area. In the long term, this traumatic event increases insecurity, thus increasing citizens' fear, anger, despair, mistrust of the institutions, and economic and structural hardships [10]. The spread of consequences of the damage on TIs could be very quick and disrupt large-scale territories due to the interdependence between transport networks and urban systems.

The improvement of TIs vulnerability can be seen as an important part of reducing urban vulnerability facing disasters. In a report of the United Nations Institute for Environment and Human Security (UNU-EHS), Japan was ranked 158th out of the 171 most vulnerable countries (even if it was the 4th country in terms of exposure to natural disasters). This was due to the fact that Japan has a very good capacity of mitigating the effects of a disaster, especially in regards to the three domains which include transport infrastructure [11].

Resilience assessment is a key aspect of disaster management since it is a popular and common method allowing for understanding of the capacities and performance of a complex system. The framework built for resilience assessment is frequently based on indicators, which help in the cognitive research of complex systems. Over the last decade, the use of indicators has been increasingly developed in urban resilience studies and CIs management [3,12–16]. Indicators are valued due to their ability to characterize CIs facing disruptions or shocks, and to support stakeholders in the decision-making process. A comprehensive analysis of indicators is particularly important for the scientists and managers of urban TIs resilience. However, the literature reviewing resilience indicators for TIs is insufficient. Therefore, this review study aims to: (1) identify and summarize the existing indicators of TIs resilience from the literature currently available; and (2) discuss the possible development of the resilience indicator of TIs. Meanwhile, this study presents a discussion about the search method for screening relevant scientific papers, and an investigation of the common characteristics of the identified TIs resilience indicators.

The definition of important terminologies is present in Section 2, which allows clarifying the scope of study interest and establishing the methodology in Section 3. Section 4 compares the number of relevant scientific papers with different keywords, while Section 5 discusses the relevancy of the screened papers. The investigation of the resilience indicators in the screened papers presents in Section 6 before the discussion and conclusion.

## 2. Terminology

### 2.1. Definition of Resilience

The term “resilience” is used in many disciplines and is difficult to define due to its very broad use. Many resilience studies argue that Holling first introduced the concept for studying ecological science. Holling [17] defined the term “resilience” as a persistent ability to absorb change and disturbance and still maintain the same state variables. Over time, a series of interpretations of resilience has been presented. Holling [18] gave further explanation of resilience in differing engineering resilience and ecological resilience: the former focuses on a stable equilibrium and the rate at which a system returns to steady-state following a perturbation; the latter focuses on processes and can be measured by the magnitude of disturbance. Walker et al. [19] presented another resilience for socio-ecological systems (SEs), defined as a region in a state-space (state of variables that constitute the system) in which the system tends to remain, and assumed four crucial aspects for resilience:

- Latitude, or the maximum amount a system can be changed before losing its ability to recover
- Resistance, meaning the ease or difficulty of changing the system

- Precariousness, or how close the current state of the system is to a limit or threshold
- “Panarchy”, following the theory introduced by Holling and Gunderson [20], referring to a cross-scale, nested set of adaptive cycles. These cycles differ in range and duration, and the larger and slower cycles generally maintain system integrity in constraining the smaller and faster ones [21].

Folke [22] discussed these three types of resilience (engineering resilience, ecological resilience, and SESs), in summarizing their characteristics, focus (properties) and contexts (spatial environment). Resilience alliance considered resilience concerning social-ecological systems that have the capacities to absorb or withstand perturbations and other stressors such that the system remains within the same regime, essentially maintaining its structure and functions. In the context of hazards and disasters, the United Nations International Strategy for Disaster Reduction (UNISDR) presents another definition: “resilience is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from disasters timely and efficiently including through the preservation and restoration of its essential basic structures and functions through risk management [23].” This idea focuses on the social system through emphasis on the necessary resources and its abilities to organize itself both before and during times of need.

Furthermore, from the narrower interpretation, the value of resilience can be described through the capabilities, such as robustness, fragility, redundancy, reliability, vulnerability, recovery, robustness, persistence, transformability, etc. [4,24–30]. In particular, Ouyang et al. [31] and Francis and Bekera [30] described CIs resilience as involving three capacities according to temporal stages (see Figure 1):

- Stage 1 refers to the disaster prevention stage, from normal operation to the onset of initial failure of an infrastructure component, that requires critical infrastructures to have the resistant capacity, to prevent potential hazards and reduce the initial damage level if a hazard occurs;
- Stage 2 refers to the damage propagation process after these initial failures. This corresponds to a system’s absorptive capacity that minimizes the damage of the hazard and the consequences, such as cascading failures;
- Stage 3 refers to the restoration response and the restorative capacity is the ability of the system to be repaired quickly and effectively.

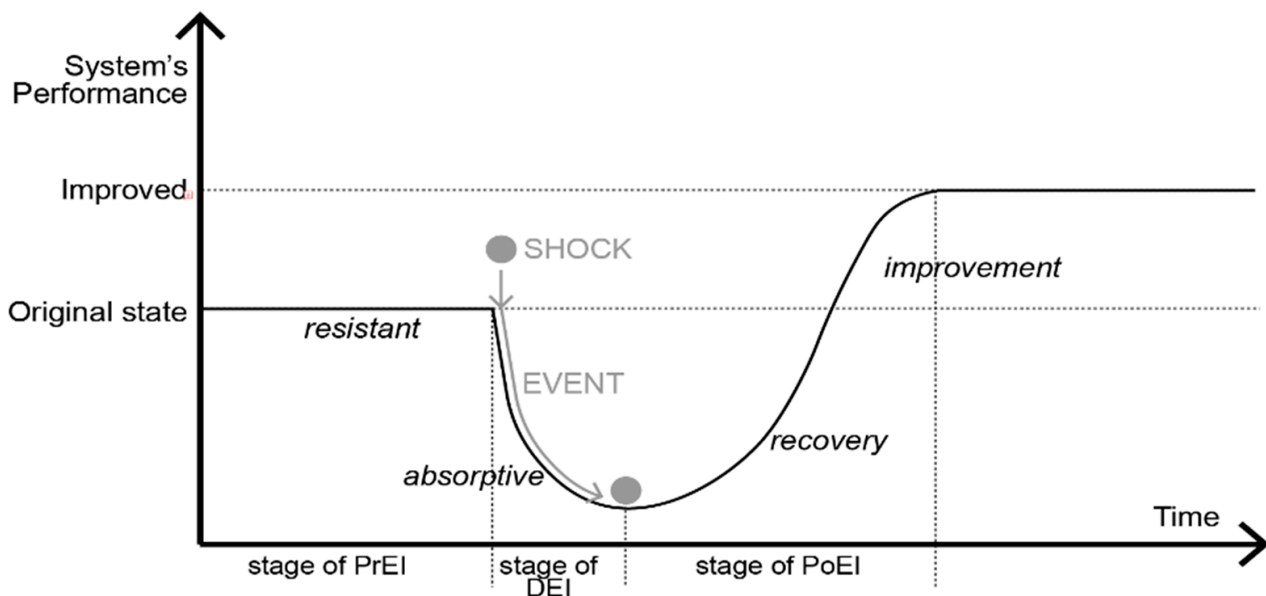


Figure 1. Urban transport performance in cycle to disruption.

### 2.1.1. Resilience in Urban Transportation

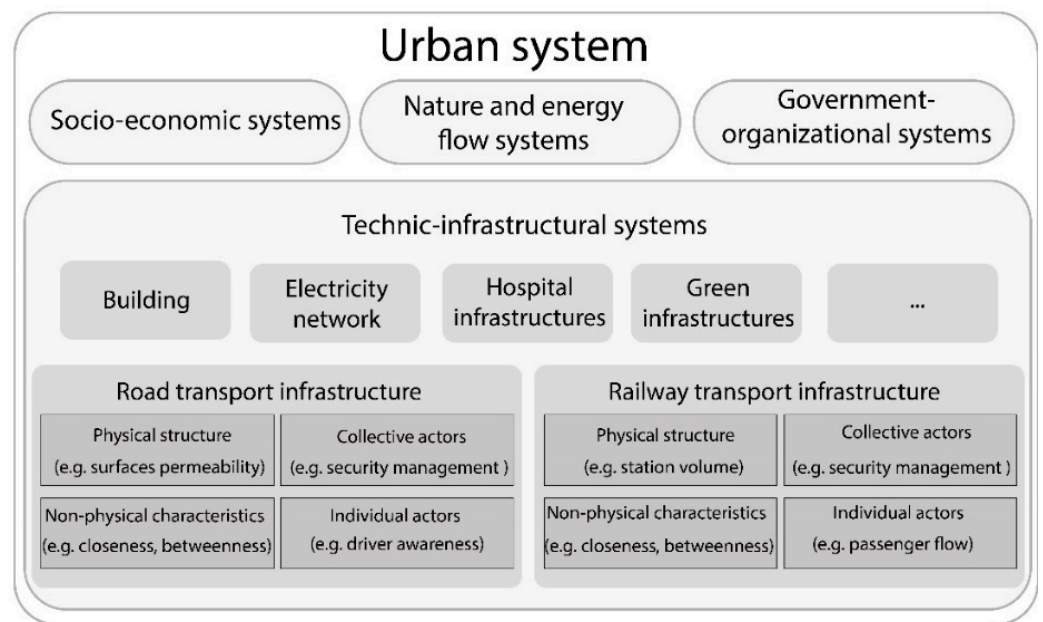
The urban TIs can be considered as a physical transport network in urban areas [7]. There is no universal description of what transport resilience is or what the standard definition it should be, since the existing studies are conducted from different perspectives [4,25]. Zhou et al. [4] reviewed the definitions of transportation resilience in 14 works found in the available literature and summarized two common perspectives: (1) the ability to maintain functionality under disruptions; and (2) time and resources required to restore performance level after disruptions.” Other definitions from three studies are presented in the following table [26,32,33] (see Table 1).

**Table 1.** Several existing definitions of resilience and assessment indicator on transport sector.

<b>(1) Definitions of Resilience of Transportation</b>	
Zhou et al. [4]	Resilience present two perspectives: (1) the ability to maintain functionality under disruptions, and (2) time and resources required to restore performance level after disruptions.
Freckleton et al. [32]	Ability of the system to maintain its demonstrated level of service or to restore itself to that level of service in a specified timeframe.
Cox et al. [33]	Capacity to adapt to a variety of different stress scenarios
Ganin et al. [26]	The ability of an entity or system to recover rapidly from a severe shock to achieve the desired state
<b>(2) Definitions of Resilience Indicator of Transport Network</b>	
Chen and Miller-Hooks [34]	Resilience indicator quantifies the ability of an intermodal freight transport network to withstand and quickly recover from a disruption.
Reggiani et al. [35]	Resilience indicator represents as a challenge to monitor and control systemic network, especially through the observation of the behavioral patterns under disruption scenarios or shocks
Yang et al. [27]	Resilience indicator assesses the abilities (resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard) of a system exposed to hazards through two aspects: the consequence of hazards on road transport network; the efficacy of reactions (in whole resilience scenario) took to improve system’s resilience.

### 2.1.2. Resilience of TIs in This Study

In comparison with these definitions, this research highlights the interdependences between TIs and other related systems. In the conceptual urban system, TIs are part of CIs, which are a significant portion of urban systems [36–38]. Moreover, TIs can be divided into a series of component systems (see Figure 2). For example, the function of a road transport system relies on all its components, such as the regulatory system, the drainage system, the maintenance system, etc. [36]. TIs resilience is connected to the function of all relevant systems. The interdependence makes all urban systems interact with and influence one another. This study considered not only the capacities of one system but also the relationships between relevant systems. Consequently, this study suggests defining urban TIs resilience as the ability of a transport network to manage multiple-equilibrium with other urban systems, to resist and absorb all shock events, to maintain and restore rapid functions whatever disruptions, to learn and improve capacity to cope with future risks.



**Figure 2.** Internal and external systems of TIs, inspired by Yang et al. [36].

### 2.2. Definition of Indicator

An indicator is something that shows what a situation is like, according to the Cambridge Dictionary. In the American Dictionary, it can be a sign or signal that shows something exists or is true, or that makes something clear. In the context of management and evaluation, an indicator provides information to measure characteristics, assess performance and evaluate capacities. An indicator, understood as a description of how to measure an issue, is the chosen information associated with a criterion, intended to observe its evolution at defined intervals [27,39].

#### 2.2.1. Indicator for Resilience Assessment

The development of resilience indicators was inspired by the adaptation practice and science of vulnerability indicators [40]. The vulnerability indicator came originally from the sustainable development study of Gallopin, which argued that indicators are not values, but variables that are an operational representation of an attribute [41]. Based on the study of Gallopin, Birkman [42] defined vulnerability indicator for natural hazards as an operational representation of a characteristic or quality of a system and a tool that provides various information and data. For adapting to different perspectives of the resilience concept, as well as variously better methods to improve resilience, resilience indicators have been defined and redefined [40]. Yang et al. believed that resilience indicators assess the abilities (resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard) of a system exposed to hazards through two aspects, consequence and reaction [27]. Lhomme et al. used a resilience indicator studying the functionality of systems during disruption, and the capacity of these networks to recovery service [43].

Over the last decade, the resilience indicator has been a practice tool to assess or measure the resilience of CIs. Indicators are typically used to assess relative levels of resilience, either to compare between places or to analyze resilience trends over time [44]. Besides, resilience indicators, whether they are presented logical values or numerical, should be clear, realistic, unambiguous, measurable, tangible, standardized, harmonized, and performing, which build its pivotal role in defining, selecting, and assessing the value of a complex system [45]. The resilience or vulnerability indicators are possibly already applied in related disciplinary of climate change, such as natural risk, human security, environmental sustainability, etc. [46,47].

As we explained in Section 2.1, resilience can be described by its capabilities, and therefore they could be the assessed subjects of resilience indicators [1,33,48–53]. For example, Cox et al. [33] argued that the indicators, “Network Topology, threaten”, “Dependence on single resource” and “Tactical vulnerability” could be used to assess the vulnerability of transportation resilience. Reed et al. [48] assessed the quality of CIs resilience in applying two indicators: power delivery capacity and time in days post-event. Enjalbert et al. [50] assessed the quality of transportation system resilience through three indicators: time during safety performance decrement, time on maximum effect of disturbance, time during safety performance recovery. Lhomme et al. [51] used two indicators, independency path and point transitivity, to assess redundancy of urban technical networks resilience. The mentioned indicators are used to assess directly the capabilities of resilience, and to assess indirectly resilience. Whereas qualifying or quantifying resilience through these capabilities could be an important step in resilience assessment. As the focus of the paper is on the indicators analysis, this step is not further described.

### 2.2.2. Indicator for Transport Network Resilience

The description of resilience indicators referring to TIs is concentrated in its function and utilization (see Table 1). Chen and Miller-Hooks [34] used an indicator for quantifying the ability of an intermodal freight transport network to withstand and quickly recover from a disruption. Reggiani et al. [35] argued that vulnerability indicators are applied to observe the behavioral patterns under disruption scenarios or shocks in transport networks, in order to monitor and control networks. Yang et al. emphasized the operation of resilience indicators that on evaluating the consequence of hazards on the road transport network and the efficacy of reactions (in whole resilience scenario) took to improve the system’s resilience [27].

### 2.2.3. Resilience Indicator in This Study

According to the state of the art, resilience indicators in this study are concerning two objectives: the consequences of shocks events on TIs; and the abilities of TIs to resist and absorb all shock events, to maintain and restore rapid functions whatever disruptions, to learn and improve capacity to cope with future risks. Moreover, this study focuses on the interdependence of infrastructure systems, emphasizing the use of resilience indicators on assessing TIs abilities to manage multiple-equilibrium with other urban systems in all stages of the resilience scenario (i.e., disruption cycle (before, during and after disruption)).

## 3. Three Steps of Literature Search Methodology

To identify existing indicators, in this paper, this study employ the Systematic Reviews method, which is common in scientific research. This method can address research questions, and uncover areas by integrating the findings and perspectives of numerous empirical studies [54]. The methodology applies three steps inspired by several articles [4,55,56] before a detailed and complete analysis.

### 3.1. Step 1: Key Word Selection

Identification of the keywords, based on the clear objectives of the review and the articulated specific research questions or hypotheses, is the first step in the review process. The “urban infrastructure” is the first chosen keyword since urban TIs are the focus of this study. According to the Cambridge Dictionary, the term “transport”, also called “transportation”, refers to the process of transporting people or things from one place to another, or a system of vehicles, such as buses, trains, aircraft, etc. for getting from one place to another. However, this definition of “transport” is not representative of TIs, which means a system or a group of connected parts of critical infrastructures. Therefore, this step searched also with terms “transport network” and “transport system” that are more suitable to this research. Meanwhile “urban”, “resilience”, “indicator” are also the critical keywords for this study.

### 3.2. Step 2: Scanning Scientific Database to Screen Papers

Two leading electronic databases, WEB OF SCIENCE and SCIENCEDIRECT, are selected for articles review. On Web of Science, search strings “urban”, “resilience”, “indicator”, “transport infrastructure” are picked as “Topic” items, with the conjunction “and”, to conduct the search work in the first round. The term “transport network” and “transport system” are replaced by “transport infrastructure” in the second and third rounds of the search. The absent “Topic” items on SCIENCEDIRECT were changed by “Title, abstract or author-specified keywords”. Therefore, the search work refers to search strings “urban transport infrastructure resilience indicator”, “urban transport network resilience indicator” and “urban transport system resilience indicator”. To understand the popularity of this topic, this study analyzed different combinations of selected keywords.

### 3.3. Step 3: Selecting Suitable Papers

After the first search in electronic databases, the selecting step aims to eliminate those that do not fit the research theme. The research result relying on keywords has a common problem: some found publications are not suitable for study objectives even though they have all keywords in their topics. For example, an unsuitable article, discussing impacts assessment of local resilience strategies to the urban transport network, could have “urban”, “resilience”, “indicator” and “transport network” as a topic keyword. Therefore, before the investigation of indication, this step helps select suitable articles in identifying the objective and goals of each screened article. Besides, resilience measurement and evaluation need to be remarked due to their important role in the resilience assessment. Resilience assessment is a process of understanding the state or condition of an issue by application of appropriate methodologies to measure, evaluate, and manage that ability in systems [57]. A relevancy analysis is created to select suitable articles screened from the electronic database.

## 4. Searching Result and Quantity Analysis

The databases selected in WEB OF SCIENCE and SCIENCEDIRECT are before 6 pm, 08 February 2022. In WEB OF SCIENCE, 40 publications are screened, while in SCIENCEDIRECT, 17 suitable articles are careened (see Table 2). Consequently, 29 articles will be discussed in relevancy analysis, since some articles of them repeat and two articles are not available on the online science website.

**Table 2.** Searching details and number of publications.

Database	Search Items	Search Strings	Number	Total	
WEB OF SCIENCE	“Topic”	“urban”,	“transport infrastructure”	7	29
		“resilience”,	“transport network”	17	
		“indicator”	“transport system”	16	
SCIENCE DIRECT	“Title, abstract or author-specified keywords”	“urban transport infrastructure resilience indicator”	6		
		“urban transport network resilience indicator”	3		
		“urban transport system resilience indicator”	8		

For understanding the popularity of the study topic in the scientific discipline, this study apply to search for different combinations (conjunction “and”) of keywords as “Topic” on WEB OF SCIENCE” and “Title, abstract or author-specified keywords” on SCIENCEDIRECT:

- Category 1: combinations of “urban”, “resilience” and “indicator”
- Category 2: combinations of “transport infrastructure” and keywords of category 1
- Category 3: combinations of “transport network” and keywords of category 1
- Category 4: combinations of “transport system” and keywords of category 1

The result is shown through the state of the art (see Figure 3). The orange part (row 10, 17, 24) is the search work mentioned above (Table 2) and discussed in Sections 4 and 5. Only a small proportion of studies on urban resilience (row 2) or urban transport (rows 4,



11, 18) are related to the resilience of urban transport (rows 8, 15, 22). In addition, less than 2 in 1000 studies on resilience indicators (row 3) are relevant to TIs (row 9). Overall, the studies on resilience indicators for TIs account for only about 3.7 per 1000 urban resilience studies (row 2).

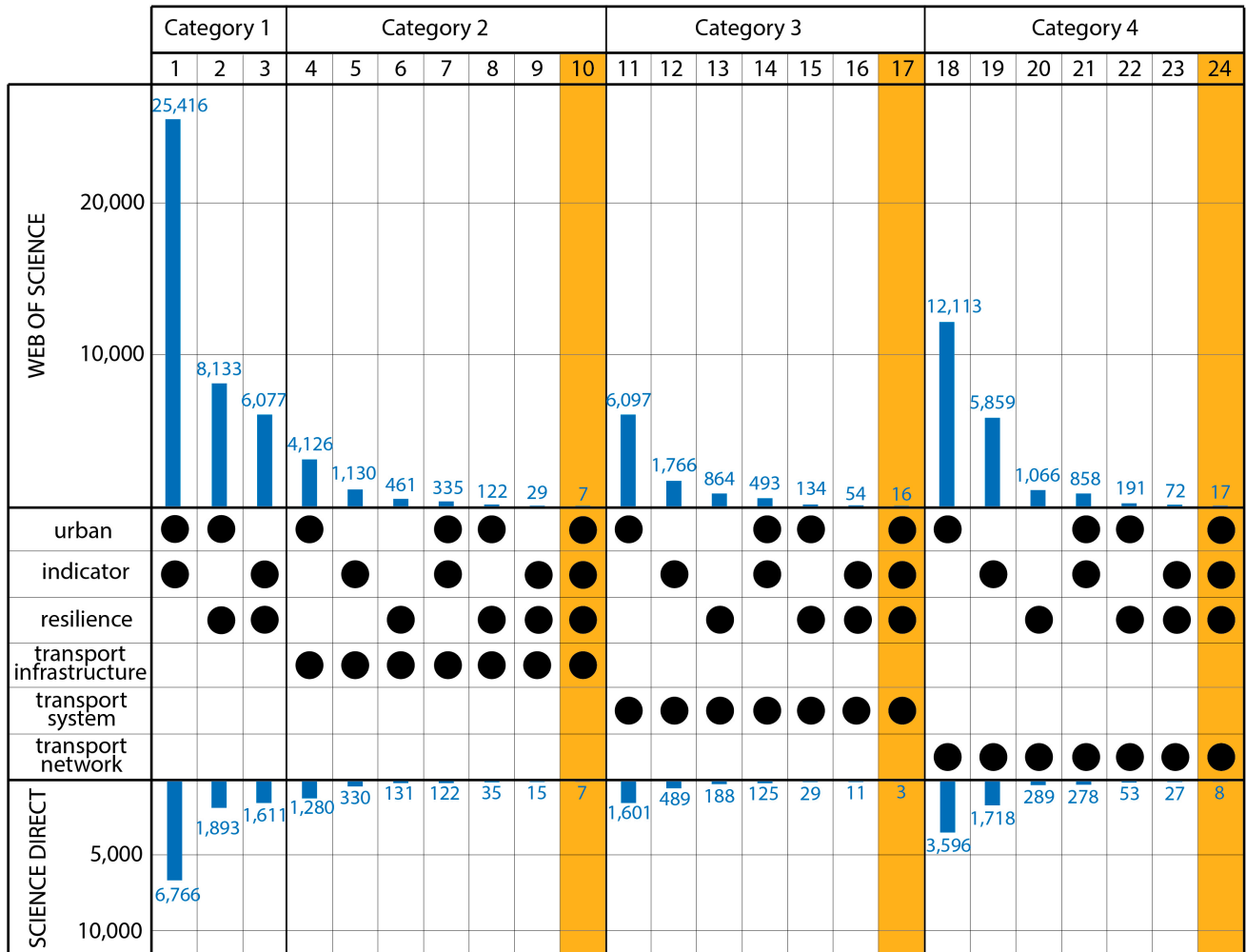


Figure 3. State of the art of the search work.

### 5. Screening Result and Relativity Analysis

These articles screened on resilience assessment indicators of TIs are multidisciplinary and cover different subjects. However, most of the articles are not suitable for the interest of this study (see Table 3). For example, Fonseca et al. [58] describe the concept of transportation resilience indicator, which assesses the ability of an urban system to reduce the number of people affected by traffic noise and to reduce the economic cost for transportation noise. Resilience refers to the ability of a system to maintain its state facing shocks. The shocks on TIs and the abilities of TIs to shocks are necessary conditions for the concept of TIs resilience [27]. Therefore, the indicators presented by Fonseca et al. [58] are for assessing the resilience of the urban economic system to the effects of transportation, rather than the resilience of TIs. Moreover, Cariolet et al. [13] assess the resilience of urban areas to traffic-related air pollution by indicators. Vajjarapu et al. [59] and Vajjarapu and Verma [60] assess the adaptation of policy strategies for urban transportation.

According to the relevance to this study, the screened articles are divided into four relevancy levels (RL):

1. This article is about assessing urban TIs resilience by indicators;
2. This article is about assessing resilience (except TIs resilience) by indicators;

3. This article is about assessing one or more object targets (except resilience) by indicators;
4. This article is not about indicators assessment.

Only the studies in the first level are related to the resilience indicator of TIs. Meanwhile, the assessment of resilience capabilities mentioned in Section 2.1 are equally suitable to the first level. Finally, seven articles are selected after the relevancy analysis (see Table 3).

**Table 3.** Relevancy levels of screened papers.

Reference	RL	Assessed Target of the Studies in Level 1–3; Objective of the Studies in Level 4
Da Mata Martins et al. [61]	1	Road network resilience
Vajjarapu and Verma [60]	3	Adaptation of policy strategies
Esfandi et al. [62]	2	Energy resilience
Lu [63]	1	Railway resilience under different operational incidents
Tromeur et al. [64]	2	Environmental system resilience
Cats et al. [65]	1	Public transport robustness
Shelat and Cats [66]	1	Spatial extent of link disruption impacts in urban public transport networks
Cariolet et al. [13]	2	Resilience of urban areas to traffic-related air pollution
Gil and Steinbach [67]	1	Indirect impact of flooding of the urban street network
Santos et al. [68]	2	Resilience and vulnerability of public transportation fare systems (not infrastructure)
Jang et al. [69]	1	Vulnerability of network-based systems (road network, for example)
Zhang and Ng [70]	3	Node criticality of public transport
Liu et al. [71]	1	Reliability in urban rail transit network facing links capacity reduction
Ortega-Fernandez et al. [72]	3	Possibility of transforming a city to a smart city
Duniway et al. [73]	3	Transportation (no infrastructure) impacts on rangelands
Enjalbert et al. [74]	4	Assessment of transport system through a framework with resilience abilities as criteria
Xu and Xue [75]	2	Chinese urban critical infrastructure resilience
Oliver et al. [76]	3	Perceptions of flooding, resilience to flooding, and the availability of critical services
Östh et al. [77]	2	Regional economic resilience
Gromek and Sobolewski [78]	2	Consequences on infrastructures to particular events
Venkatesh et al. [79]	2	Urban water system
Watcharasukarn et al. [80]	4	Explore private travel adaptive capacity by a role playing computer game concept
Olowosegun et al. [81]	3	Quality of service of informal public transport
Fonseca et al. [58]	3	Spatial heterogeneity
	3	Performance of environmental system (impacts of energy and transport system on environmental system)
	2	Resilience of the energy system
	2	Resilience of economic system facing noisy pollution from transportation systems
Vajjarapu et al. [59]	3	Adaptation of policy strategies
Xiao and Yuizono [82]	3	Landscape microclimate environment
Leung et al. [83]	2	Vulnerability of transport oil
Bowering [84]	3	Mobility of ageing people
Adlakha and Parra [85]	3	Physical activity

## 6. An Indicators' Overview in Selected Papers

In this section, the seven selected articles are further investigated through five aspects: dimensions, temporal stages of indicators, focus systems (internal or external), use of sub-indicator and spatialization.

### 6.1. Dimension of Indicators

IMPROVER project presents three 'domains' of critical infrastructure resilience, that is, social, organizational, and technological [21]. This study suggests the fourth domain, namely the environmental domain. Therefore, all resilience indicators are mainly divided into four categories:

- Socio-economic indicator (SEI), which refers to human, social and economic information;
- Organizational indicator (OI) which represents the information of the management of institutions and the organization of resources;
- Technical indicator (TEI), which refers to the state or situation on technical facilities and networks;
- Environmental indicators (EI), which refers to natural and environmental resources or statistics.

Sometimes an indicator corresponds to several domains. In this study, the point of view of the author is the most important criterion to identify the dimension of resilience indicators. In addition, this study consider the content actual of indicators, their applicable users, and the purpose of indicator studies.

### 6.2. Indicators' Temporal Stages

From the perspective of the event occurrence, CIs resilience is a refocus from protection to adaptation and recovery of a system. Based on the theory of Ouyang about the temporal stages [31], TIs resilience indicators are categorized as pre-event indicators (PrEI), during event indicators (DEI) and post-event indicators (PoEI). In our study, the event is defined as the occurrence by which a shock causes maximum impact to transport system' performance (see Figure 1):

- Pre-event indicators (PrEI), which assesses the resistance capacity and refers to the disaster prevention processes before the occurrence of events.
- During event indicators (DEI), which assesses the absorptive capacity and refers to the damage propagation processes during the occurrence of events.
- Post-event indicators (PoEI), which assesses the restorative and improvement capacity and refers to the recovery and improvement processes after the occurrence of events.

### 6.3. Position of Focus System

As introduced earlier, infrastructure resilience should not be limited to stand-alone infrastructure systems. Based on the study of Yang et al. [36] about the interdependence of CIs, this study distinguishes the resilience indicator of TIs to internal indicator and external indicator. The former focus on the target system or its components, while the latter focus on the external systems of the target transport network. The resilience indicator of internal TIs refers to assessing the resilience of internal components, categorized as physical structure, non-physical characteristics, collective actors, and individual actors. The example indicator of each category is shown in Figure 2

### 6.4. Sub-Indicators

Resilience assessment is a complex process in which indicators could be measured with different metrics. Sometimes, to further explain an indicator, many studies use sub-indicators, all of which are measured to complete the metric of an indicator. The metric of indicators is based on the collection of reliable data and is used to evaluate or measure one or more capabilities of the resilience system and to observe whether they meet the criteria.

### 6.5. Spatialization of Infrastructure Resilience Indicators

Geography plays a crucial and indispensable role in many decision-making processes, especially for cities and the components of the urban system. Resilience mapping can be used to assess the strengths and weaknesses of the city's resilience [85–87]. The review study from Cariolet et al. [13] mapping urban resilience to disasters emphasized the central role of resilience indicators for specific units of resilience analysis (district, region, state, etc.). The spatialization of indicators allows the value of resilience to be spatialized, thus assessing vulnerabilities and resilience of different urban territories. That, therefore, makes indicator mapping important for decision-makers to recognize problems, find solutions and thus help to define corrective or preventive actions for future risks.

### 6.6. Results of Indicators' Analysis

Da Mata Martins et al. [61] assess the absorptive capacity of mobility resilience with the following indicator: possibility of changing the modes based on motorized vehicles to active modes in case of a given shock leading to a disruption in TIs. The indicator is measured with the maximum possible distances (MPD) possible by walking or cycling mode. The collected information is about the origin-destination (OD) datasets of the road network (internal system) and social risk sensitivity to motorized transport modes (based on population physical/health condition, along with terrain using the street gradients, road network topology). In the last step of his study, Da Mata Martins et al. [61] map the distribution of resilient trips to apply the outcome to urban planning at a strategic level.

Lu [63] demonstrates a resilience approach for understanding the absorptive and recovery capacities of rail transit networks under daily operational incidents. This study is based on the OD flows of the transport network, and the measure of importance-impedance degradation under incidents. Lu focuses on the changes of the rail transit network before the system return to the original state, with (1) the time duration of incidents and (2) the impacts on delayed travel demand during the perturbation (performance below original state). With a map of indicator value, Lu compares the resilience rail network sector in the central area and suburban area of Shanghai.

Cats et al. [65] and Shelat and Cats [66] assess the robustness of the public transport system through TEIs: the former focus on two indicators, namely link criticality and degrading rapidity; the latter assesses the spill-over effects by link criticality and the system performance by generalized travel cost criticality. The robustness is one of the resilience capacity and refers to the ability of the system to withstand a given level of stress or demand without suffering degradation or loss of total function. Cats et al. [65] and Shelat and Cats [66] present the indicators on the map of Amsterdam's urban rail public transport network.

Gil and Steinbach [67] and Jang et al. [69] assess indirect consequences of hazards on the road network by measuring its performance changes in terms of spatial accessibility (closeness) and path overlap (betweenness). The indicators of Gil and Steinbach [67] do not only address the technical information of TIs, the network-based paths and nodes, but also the social information, the urban street morphology (in New Orleans). Different from Gil and Steinbach [67], Jang et al. [69] focus mainly on network-based information and calculate average node degree, cumulative degree distributions to measure two indicators, degree centrality, and betweenness centrality. The indicators spatialization in the study of Jang et al. [69] presents the average node degree in twenty-five districts in Seoul.

Liu et al. [71] assess the reliability of urban rail transit network facing links capacity reduction. The study suggests a model formulation of passengers' generalized travel cost, which is the sum of the monetary and nonmonetary costs of a trip. The nonmonetary costs refer to perceived travel time, including waiting time, walking time, in-vehicle time, and transfer times. The value of monetary costs is estimated by the household income per hour of population.

The summaries of the seven selected articles are in the following Table 4. Most of the indicators focus mainly on the "during stage" of the resilience scenario, and the internal

systems of the TIs. All of the indicators concern technical information; a few concern social information and none concern organizational and environmental information. Six of the seven studies use sub-indicators and analyze indicator spatialization.

**Table 4.** Summary of the seven selected articles.

Reference	Da Mata Martins et al. [61]	Lu [63]	Cats et al. [65]	Shelat and Cats [66]	Gil and Steinbach [67]	Jang et al. [69]	Liu et al. [71]
Indicators	Possibility of changing the modes	Importance-impedance degradation of critical stations	Spatial criticality, Degradation rapidity	Spatial criticality, Travel cost criticality	Performance	Degree centrality, Betweenness centrality	Passengers' generalized travel cost
Type	Road	Railway	Railway	Railway	Road	Road	Railway
Dimension	TEI SEI	TEI	TEI	TEI	TEI SEI	TEI	TEI SEI
Stage	DEI	DEI PoEI	DEI	DEI	DEI	DEI	DEI
Position	Internal system, External social system	Internal system	Internal system	Internal system	Internal system	Internal system	Internal system, External social system
Spatialization	Yes	Yes	Yes	Yes	Yes	Yes	No
Sub-indicator	Maximum Possible Distances of three types of trips	Duration time of different incidents, Characteristics of the failed stations	Travel cost: average travel time, share of disconnected demand or delayed passengers	No	Spatial accessibility (closeness), Path overlap (betweenness)	Average node degree, Cumulative degree distributions	Monetary and nonmonetary costs of a trip

## 7. Discussion

### 7.1. Identified Existing Indicators

The analysis of the identified indicators above shows the characteristics of the existing resilience indicators of TIs.

Firstly, the assessment of the connection between TIs and other related systems is inadequate. In modern societies where all systems are highly interconnected and interdependent, the stability of interdependencies should be also considered as part of the resilience assessment. The study of Yang et al. [36] on functional interdependence, for example, demonstrates the connection between urban road systems and emergency medical services. Secondly, insufficient focus is given to socio-economic, organizational or environmental indicators. However, multi-domain indicators exist for assessing the resilience of other CIs. Shirali et al. [88], Bialas [89], Johnsen and Veen [90], Carvalho et al. [91], Cox et al. [33], and Fisher et al. [92] discuss organizational indicators, employees' capacity to crises, learning culture, safety culture, etc. Franchin [93] Cox [33], Serre [94], Johnsen and Veen [90], Bialas [89], and LaLone et al. [95] use social indicators, such as decisions of spatial management, Twitter discussion, shelter-seeking populations, etc. De Vivo et al. [96] considers the number of green walls and roofs as an indicator to assess the resilience of airports. The application and reliability of all the above indicators should be discussed in future studies for the resilience assessment of TIs. Thirdly, all identified indicators assess the stages of "during" perturbation. The resistance and recovery capacities are less discussed. The actions of preparation and restoration play an important role to improve cognitive and learning capacities in a resilience scenario.

Sub-indicators and indicators spatialization and mapping are applied widely. Nevertheless, there is a lack of a standard systematic framework for the hierarchy and categorization of indicators. To enable users to better apply indicators in practice cases, the question concerning how to structure the classification of indicators should also be investigated. Additionally, geographic information systems (GIS) have been a powerful tool for presenting and analyzing layers of information [87]. The question concerning how to improve the method of indicators spatialization based on GIS application has become an essential challenge for the future.

### 7.2. Search Method with Keywords

This paper is based on a literature search online. However, the search work may be limited by the selected keywords. Based on an observation on resilience assessment

framework, some studies on resilience indicator of TIs could not be screened in electronic databases with the keywords “indicator” [50,53,97]. Some studies use terms or vocabularies similar to “indicators”, such as index, indices, parameter, metrics, but they fit the definition of “indicator” in this study [33,98]. Some studies use variables to assess resilience, such as time, performance, damage, costs [99–101]. These variables are indicators, but they cannot be found with the keyword “indicator” either. Therefore, the indicators identified by the search method with the keyword “indicator” are not all existing indicators. Furthermore, according to a test, more articles could be screened if the search work adds these similar vocabularies and variables as keywords. However, few articles are suitable for study objective and it still requires manual selection, since the definitions and usage of these similar vocabularies or variables are not completely the same as “indicator”. This shows that the automatic search method has barriers in practice application. The method used in this study makes it possible to screen articles with the “resilience indicator of TIs” as the core of the study, and not to identify all “resilience indicator of TIs”. To select more relevant literatures, two additional methods are suggested to be considered in the future: the reference of relevant studies or suggestions from experts.

## 8. Conclusions

Over the past decade, the emphasis of the concept of resilience has been well enhanced among urban managers and scientific studies. In particular, the resilience of CIs and TIs have become the important aspect to improve the city’s performance. Undeniably, on both scientific and practice domains, there is a growing effort devoted to assess the resilience of TIs. However, as an internationally recognized method, the indicators assessment has not been integrated into a standard system to help describe the resilience of TIs. This study presents a review and a summary of the existing resilience indicators for TIs, which allow one to highlight the characteristics and possible development of indicators assessment. Additionally, this paper introduces a new definition of TIs resilience that provides a new perspective about future resilience indicators.

The limit of this study is its search method, potentially leading to inadequate screened scientific papers. Broadening the searching words or using other search methods is necessary. Other future studies could focus on practice indicators in the regulatory frameworks, guides, reports, and other non-scientific documents. Besides, the application of indicators seems indispensable. Concrete steps could include indicators collection, indicators identification, indicators calculation, indicators mapping, etc.

**Author Contributions:** Conceptualization, Z.Y. and B.B.; methodology B.B. and Z.Y.; investigation and writing—original draft preparation Z.Y.; writing—review and editing A.B.-D., H.D. and B.B.; visualization, Z.Y. and B.B.; supervision B.B., A.B.-D. and H.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors performed this work with funding from the UrbaRiskLab (URL) project (<https://urbarisklab.org/fr/>, accessed on 10 January 2022) and the RESIIST project (ANR-18-CE39-0018, <https://researchgi.mines-albi.fr/display/14esist/RESIIST+Home> (in French), accessed on 10 January 2022) that is jointly funded by the French National Research Agency (ANR) and the General Secretary of Defense and National Security (SGDSN). The authors acknowledge these organizations for their support that helped improve the paper.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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