Technical Note

Recent Advances in Modeling the Vulnerability of Transportation Networks

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Abstract: It is well known that for major infrastructure networks such as electricity, gas, railway, road, and urban water networks, disruptions at one point have a knock-on effect throughout the network. There is an impressive amount of individual research projects examining the vulnerability of critical infrastructure network. However, there is little understanding of the totality of the contribution made by these projects and their interrelationships. This makes their review a difficult process for both new and established researchers in the field. To address this issue, a two-step literature review process is used to provide an overview of the vulnerability of the transportation network in terms of four main themes—research objective, transportation mode, disruption scenario, and vulnerability indicator—involving the analysis of related articles from 2001 to 2013. Two limitations of existing research are identified: (1) the limited amount of studies relating to multilayer transportation network vulnerability analysis, and (2) the lack of evaluation methods to explore the relationship between structure vulnerability and dynamical functional vulnerability. In addition to indicating that more attention needs to be paid to these two aspects in the future, the analysis provides a new avenue for the discovery of knowledge, as well as an improved understanding of transportation network vulnerability. **DOI:** 10.1061/(ASCE)IS.1943-555X.0000232.

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Introduction

The overall objective of most national traffic policies of today is to provide society with an economical and sustainable transportation network (Berdica 2002). However, there are many possible sources of degraded network performance, ranging from adverse weather to planned road works, as well as intentional harm arising from conflicts in labor relations or terrorist actions. Together with these, the increased complexity of the networks themselves and adaptive behavior of travelers, traffic congestion and other types of failures and delays can develop, causing significant economic and social consequences.

Such issues, termed the vulnerability of transportation networks, have been the subject of a wealth of research. This problem has now reached the point where a systematic analysis of academic journal articles is needed to assist researchers in exploring the current status and future trends (Tsai and Wen 2005). Several reviews have been conducted in the more general field of vulnerability of networked infrastructures. Murray et al. (2008) and Grubesic et al. (2008) conducted content analyses of vulnerability in the field of networked critical infrastructure. These analyses focused on networked critical infrastructure and methodologies for evaluating vulnerability. However, transportation networks are very different from other critical infrastructure, as their dynamic character is that of a carrier of agents. Other studies involve content analyses of the vulnerability, reliability, and robustness of degraded transportation networks, aiming to explore different definitions of vulnerability, reliability and robustness (Berdica 2002), diversity of related terms (Berdica 2002), evaluation methodologies (Murray et al. 2008), disruption protocols (Sullivan et al. 2009), and types of indices for evaluation (Sullivan et al. 2009). Despite this existing literature, a more comprehensive content analysis of professional publications is needed to identify recent advances in modeling the vulnerability of transportation networks.

To provide a clearer picture of the current state of knowledge of future trends of the vulnerability of transportation networks, this paper presents an overview in terms of four main themes—research objective, transportation mode, disruption scenario, and vulnerability indicator—from associated publications published in journals and conferences from 2001 to 2013. Although these four research themes are considered separately for each transportation mode in most papers, the general comparison and summary not only provides a general research methodology for transportation vulnerability analysis and current state of knowledge, but also identifies areas in need of attention and provides researchers with a clear research direction for the future.

Definition: Vulnerability of Transportation Networks

The concept of vulnerability has three closely related interpretations in the literature. In the first interpretation, vulnerability is

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defined in terms of the idiom *little strokes fell great oaks* (T. Abrahamsson, "Characterization of vulnerability in the road transport system," working report), i.e., a relatively small incident can, if it happens in an unfortunate (critical) place and time, cause major damage or even the failure of the whole system through chain reactions. The second interpretation of vulnerability concerns *risk*. The vulnerability of a road transportation system is its susceptibility to incidents that result in considerable reductions in road network serviceability. The serviceability of a link/route/road network describes the possibility of using that network during a given period (Berdica 2002). The management of road network vulnerability involves an all-embracing framework that identifies a spectrum of incidents and collects data on probabilities and consequences to estimate risks, etc.

The third interpretation of vulnerability is partitioned into two components of probability and consequence (Erath et al. 2009; Jenelius 2009; Johansson and Hassel 2010; Tampère et al. 2007). The difficulty in estimating the probability of rare events is realized by researchers (Johansson and Hassel 2010) and only condition consequences and conditional criticality of components are assessed (Jenelius et al. 2006; Jenelius and Mattsson 2012).

By analyzing the origin of the word *vulnerable*, vulnerability is used to describe a kind of Achilles' heel—a deadly weakness in spite of an overall strength that can potentially lead to a downfall. Vulnerability is an inherent attribute of any system (Haimes 2006; Hood et al. 2003; Li et al. 2008). The probability of an incident may obscure other potential network problems (Taylor and D'Este 2007). Vulnerability as defined in Abrahamsson ("Characterization of vulnerability in the road transport system," working report) is used by many researchers in the field of transportation network vulnerability (D'Este and Taylor 2003; Schuchmann 2010) and is also adopted here. With this definition, therefore, the vulnerability of transportation networks should answer three questions:

- Is there a weak component or geographical location whose failure would cause major damage?
- How vulnerable is the network when the critical components or locations are damaged?
- To what types of disruption is transportation network vulnerable?

It is also helpful to define the relationship and difference between vulnerability and risk, reliability, robustness, flexibility, and resilience of transportation networks under disruption etc., which are all concerned with incidents that transform a normal operation system into an abnormal one. The most common of these are summarized in Table 1, with their interrelationships presented in Fig. 1.

Table 1. Definition and References of Vulnerability Terminologies

Term	Definition	Reference
Risk	Risk is expressed as the probability of occurrence of a certain given event multiplied by the failure probability of a given infrastructure object and the consequences	Erath et al. (2009), Haimes (2006)
Reliability	Reliability is the probability that a network will deliver a required standard of performance	Taylor and Susilawati (2012)
Resilience	Resilience is the capability to resist and recover from a disruption	Chen and Miller-Hooks (2012), Miller-Hooks et al. (2012)
Robustness	Robustness is the extent to which, under prespecified circumstances, a network is able to maintain the function for which it was originally designed	Snelder et al. (2012), Sullivan et al. (2010)
Flexibility	Flexibility is the ability of a traffic network to expand its capacity to accommodate changes in demand for its use while maintaining a satisfactory level of performance	Cho (2002)

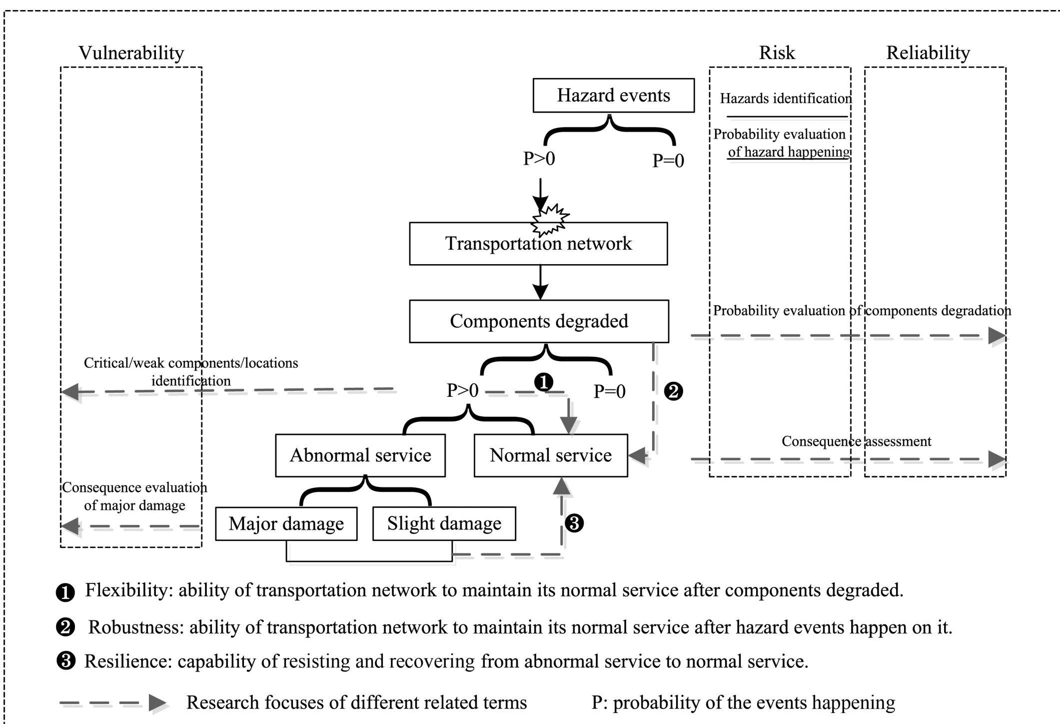


Fig. 1. Differences among the most-related terms

Research Methodology

According to the definition of vulnerability of a transportation network, studies that are related to the vulnerability evaluation of transportation networks and vulnerable (critical) components identification are considered in this review. Then a thorough review was made of publications in well-known transportation research journals, special issues, and many related conference proceedings to map the development of the vulnerability of transportation networks on the assumption that most research teams publish their findings through these high-level media. A two-step process was used as illustrated in Fig. 2.

In the first step, a comprehensive search was conducted under the *Title/Keyword/Abstract* (T/K/A) field of the search engines *Scopus* and *Web of Knowledge*. Vulnerable spot identification under disruption is considered an essential part in vulnerability transportation networks but not in risk analysis because the risk probabilities of different locations of equipment where the incidents happen are not counted separately but counted together in one kind of risk factor, such as equipment (Trucco et al. 2008). Therefore, the effects of any part (section, crossing, change station, power unit, etc.) can be not evaluated in risk analysis. Also, vulnerable spot identification is not the essential part of reliability, resilience, robustness, and flexibility analysis. If this is not the case, then words such as importance, critical, weak, and vulnerable would be used in the paper (Derek et al. 2012; Berche et al. 2009). Therefore, the full search code was as follows:

TITLE-ABS-KEY(vulnerability OR vulnerable OR critical OR criticality OR weak OR weakness OR vital OR important OR importance OR disrupt OR disrupted OR degrade OR degraded OR survivability) AND TITLE-ABS-KEY(transportation OR infrastructure OR road OR subway OR highway OR rail OR airline OR bus OR waterway) AND TITLE-ABS-KEY(network) AND TITLE-ABS-KEY(component OR link OR node OR station OR track OR location)) AND PUBYEAR > 2,000 AND (LIMIT-TO (DOCTYPE, *ar*) OR LIMIT-TO(DOCTYPE, *re*) OR LIMIT-TO (DOCTYPE, *ip*) AND [LIMIT-TO(LANGUAGE, *English*)] AND [LIMIT-TO(SRCTYPE, *j*) OR LIMIT-TO(SRCTYPE, *k*) OR LIMIT-TO(SRCTYPE, *b*)].

In the second step, a content analysis of the selected papers was carried out to identify common research processes in vulnerability related studies. A critical review of the research objectives, transportation modes, disruption scenarios, and vulnerability indicators was carried out to ascertain any changes, trends, and areas yet in need of study.

Results

There has been significant effort directed at developing methods and approaches for exploring the potential outcomes of unscheduled losses for transportation networks. The vast majority of this effort focused on staging a hypothetical network disruption and then assessing its impact on network performance (Sullivan et al. 2010). The purpose of this section is to summarize what is depicted in the vulnerability of transportation networks studies.

A common research methodology adopted by researchers comprises four key stages: (1) identification of research objectives, (2) transportation mode applications, (3) disruption scenarios definition, and (4) vulnerability indicators (Fig. 3). The first step of the research methodology is normally achieved via a comprehensive literature review, investigation of the industry, and communication with other researchers to identify research objectives. After identifying the research objectives, the second step of the study would typically be the selection of the transportation mode. This mode needs an additional review, as well as an investigation into the objectives of the selected transportation mode. How to establish the transportation network, such as graph theory or geographic information system (GIS), should also be considered in the second step. The third step of the methodology typically considers *disruption scenarios* by assumption of a location, duration, time of occurrence, the capacity reduction it induces and the number of components degraded simultaneously. The final step of this methodology is normally to establish the vulnerability indicator that will then

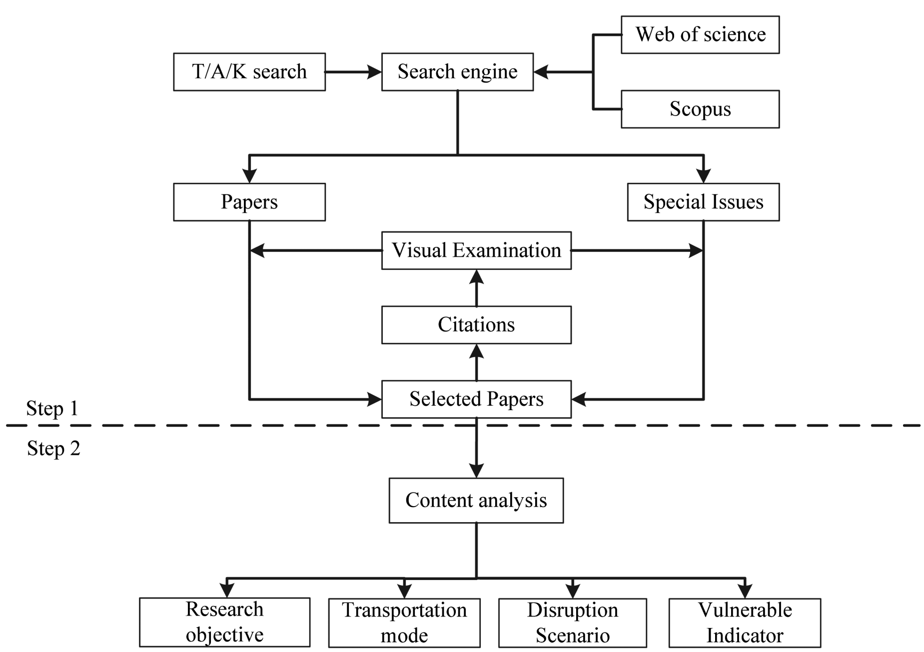


Fig. 2. Two-step research framework (adapted from Ke et al. 2009)

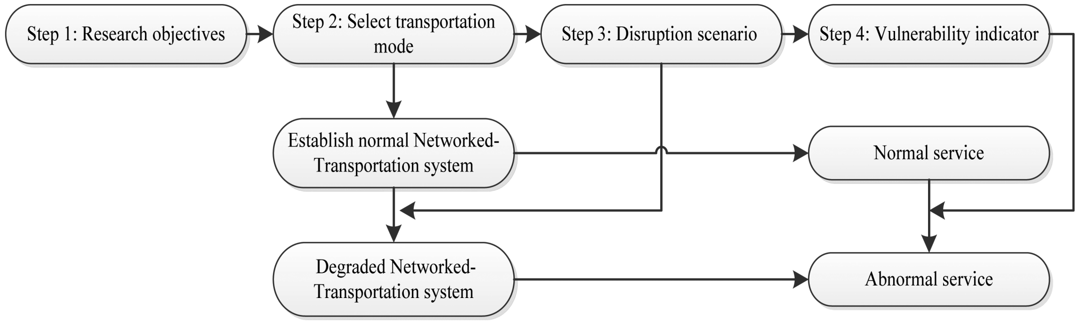


Fig. 3. General research methodology in vulnerability of transportation networks

deliver the initial findings of the research study. A content analysis was conducted from the four common steps.

Research Objectives

Through the comprehensive review of these published papers, the major research objectives and their frequencies were summarized in Table 2. Objectives 4 and 6 were conducted as essential parts in almost all previous research. However, the detailed analyses were different from the transportation modes applied by the disruption scenarios used for the failure of components or locations, as well as for the impact factors included in the vulnerability indicators. In other words, the conclusions of two research efforts with the same research objectives would be different because of the differing transportation modes, the different disruption scenarios used for the failure of components or locations, and the different impact factors included in the vulnerability indicators.

Transportation Mode

For different transportation modes, the research methodology and vulnerability characteristics are quite varied. An approach designed for a multilayer road network (Abdel-Rahim et al. 2007) cannot be applied directly to a subway network, which is a frequency-based and strictly capacity-constrained system, with the interrelationship of stations and tracks being more significant than in a road network. For example, if an incident happens at a station on Line 1, all the trains in service on this line would be affected and restricted to a lower speed when passing by the degraded station. Therefore, arrival frequency of the downstream station would also be affected. Trains on other lines sharing the same downstream station and tracks should change timetable accordingly. Additionally, the interdependent relationships of a multilayered intelligent transportation network, such as a subway or power subsystem providing traction power to the train operation system, cannot be reflected by the same approach applied to road networks.

To observe the popularity of these categories, the frequencies of the transportation mode were calculated. Table 3 indicates that multilayer transportation systems and frequency-based and capacity-constrained container transportation modes have received little attention in the literature.

Disruption Scenarios

The simulation of a disruption with specific disruption parameters on a specific link is called a disruption scenario (Burgholzer et al. 2013). A disruption is described by its location and assumptions about its duration, its time of occurrence, the capacity reduction it induces, and the number of components degraded simultaneously. In summary, there are eight types of disruption scenarios (Table 4). Arbitrary combinations of these are used in the vulnerability of transportation networks literature.

The purpose of a targeted attack is not only to simulate disruptions but also to provide a short list for simulations incorporating a full network scan approach with traffic assignments which can be computationally intensive. For example, the well-known Chicago regional network for testing traffic assignment algorithms consists of 39,018 links. For each link closure, a traffic assignment

Table 2. Major Research Objectives and Their Frequency

Number	Objective	Frequency (%)
1	Define vulnerability and other related terms	8
2	Conduct an overview of vulnerability analysis in networked infrastructure systems	6
3	Describe the vulnerability assessment process qualitatively	2
4	Estimate the impact of the loss of components and locations on the transportation network	50
5	Estimate the impact of the loss of components and locations on a particular component or locations	16
6	Identify the critical components of transportation network by calculating and ranking the impact on the whole network	33
7	Provide a candidate list of disruption scenarios	9
8	Determine how vulnerability depends on different variables	4

Table 3. Frequency of Different Transportation Modes Studied in the Selected Papers

Transportation mode	Frequency (%)
Intermodal transport network	3
Road network/highway	70
Railway network	8
Shipping network	1
Airline network	4
Subway	6
Multilayer railway network	3
Multilayer highway network	1
Public transportation network	1
Power and gas systems	1
Power and water systems	1

Table 4. Eight Types of Disruption Scenarios

Factors	Type	Citation
Degree of the closure: It is used to describe the degradation degree of one segment	Full closure	Berdica and Mattsson (2007), Hernández and Gómez (2011), Johansson and Hassel (2010), Tang et al. (2009)
	Partial closure	Chen et al. (2007), Berdica and Mattsson (2007), Luathep et al. (2011), Nagurney and Qiang (2007), Sullivan et al. (2010)
Number of disrupted components: The number of elements disrupted (single disruption and multiple) is used to describe how many segments degraded	Single component	Hernández and Gómez (2011), Jenelius et al. (2006), Yin and Xu (2010)
	Multiple components	Jenelius et al. (2006), Hernández and Gómez (2011), Jenelius and Mattsson (2012)
Disruption duration: Time duration from abnormal service to normal service	Short-term duration	Sullivan et al. (2010), Watling and Balijepalli (2012)
	Long-term duration	Masiero and Maggi (2012)
Source of disruption: The degradation of component is caused by random failure or target attack	Random attack	Jenelius et al. (2006), Qian et al. (2012), Zhang et al. (2011)
	Target attack	Knoop et al. (2012), Qian et al. (2012)

conducted on the Chicago regional network requires approximately half an hour. Consequently, the full scan approach can take about two years to identify most of the critical links in such a network. Therefore, a full network scan approach may not be viable for critical link identification in large-scale, congested road networks (Chen et al. 2012).

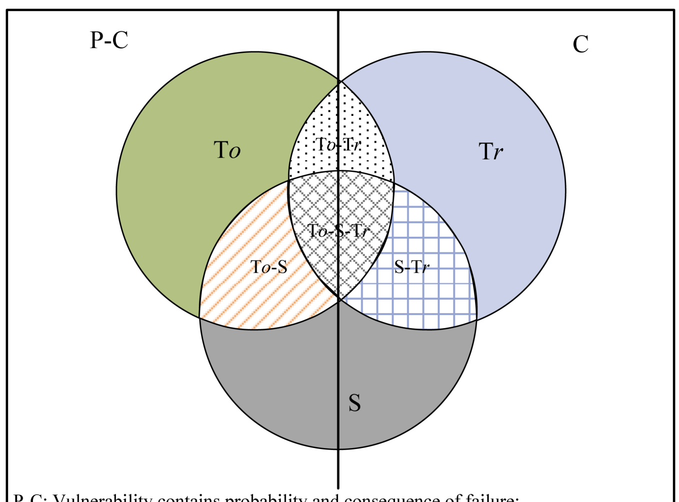
Several approaches have been introduced to overcome the computational time problem. Preselection strategies first select links or nodes that are likely to be vulnerable based on criteria including high travel load links (Burgholzer et al. 2013), the most popular routes or links for travelers (Taylor 2012; Taylor and D'Este 2007), a high probability of disruptions (Nyberg and Johansson 2013), nodes with the highest degree (Qian et al. 2012; Zhang et al. 2011), capacity and volume based indicators (Knoop et al. 2012), and node or link indicators (Schintler et al. 2007; Zhang et al. 2011).

Vulnerability Indicator

The value of the vulnerability index is used to quantify the impact of disruption events and answer the question of how system performance is explained (Burgholzer et al. 2013). The function of the vulnerability index is determined by the definition of vulnerability. As described in the "Introduction" section, vulnerability is composed of the probability of incidents and their consequences (P-C) as defined by Berdica (2002), or consequences (C) as defined by D'Este and Taylor (2003) and Abrahamsson ("Characterization of vulnerability in the road transport system," working report). Therefore, the critical analysis of the vulnerability index is classified first according to whether the probability of failure is contained in the function as P-C or C (Fig. 4).

The vulnerability of components, locations, and the network as a whole to a failure depends on which impact factors are included in the vulnerability indicator. First, a transportation system is a geospatial system in Euclidean space. Every segment of transportation has its location in this space, with specific geological conditions, facilities (hospital, school, office buildings, etc.), population densities, and so on. This Euclidean space-based factor is defined as a spatial-related factor. Secondly, in graph theory, transportation segments are represented by nodes and links, irrespective of the real location in Euclidean space and the Euclidean distance between two nodes, only considering pairwise relations between two nodes. The Euclidean distance can be reflected by the attributes of links in a weighted graph. The graph's topological characteristics in complex theory such as degree, cluster, betweenness, and efficiency (Barabási and Albert 1999) are used to describe the importance and position of the nodes and links in the network. These complex network-based factors are defined as topological-related factors. The role of the transportation system in society is to provide a travel service. However, both spatial-related factors and topological-related factors cannot solely reflect the transport function. Therefore, a traffic-related factor describes the unique attributes of a transportation system, such as traveler behavior, travel cost, traffic assignment, traffic flow on nodes and links, travel speed, capacity of road, capacity of container, frequency of container transport, etc.

In the vulnerability of transportation networks, the estimates of the impact of disruptions for components, locations, and networks are based on three types of factors: spatial-related factors, topological-related factors, and traffic-related factors, or the combination of all three (Fig. 4). Although topological factors are implicit in traffic flow and assignment, the effects of transportation network vulnerability caused by the variation of topological structure cannot be analyzed if all three factors have not been



P-C: Vulnerability contains probability and consequence of failure;
C: Vulnerability contains consequence of failure;
T*o*: Vulnerability indicator contains Topological-related factors;
T*r*: Vulnerability indicator contains Traffic-related factors;
S: Vulnerability indicator contains Spatial-related factors;
T*o*-T*r*: Vulnerability indicator contains both Topological-related factors and Traffic-related factors;
T*o*-S: Vulnerability indicator contains both Topological-related factors and Spatial-related factors;
S-T*r*: Vulnerability indicator contains both Spatial-related factors and Traffic-related factors;
T*o*-S-T*r*: Vulnerability indicator contains Topological-related factors, Spatial-related factors and Traffic-related factors.

Fig. 4. Vulnerability indicators in transportation networks

Table 5. Traffic Assignment Models Used in Studies of Transportation Network Vulnerabilities

Traffic assignment models	Citations
Noncapacity constrained networks	Berdica and Mattsson (2007), Jenelius et al. (2006), Lu and Peng (2011), Nagurney et al. (2010), Peterson and Church (2008), Scott et al. (2006), Shiomi et al. (2011), Taylor and Susilawati (2012), Taylor and D'Este (2007), Watling and Balijepalli (2012)
Capacity constrained models	Chen et al. (2012), Issacharoff et al. (2008), Jenelius et al. (2006), Jenelius and Mattsson (2012), Karlaftis and Peeta (2009), Knoop et al. (2012, 2008), Luathep et al. (2011), Nagurney and Qiang (2007)
User equilibrium model	Berdica and Mattsson (2007), Chen et al. (2012), Erath et al. (2009), Hernández and Gómez (2011), Issacharoff et al. (2008), Jenelius (2009), Jenelius et al. (2006), Nagurney et al. (2010), Qiang and Nagurney (2007), Scott et al. (2006), Shimamoto et al. (2008), Sullivan et al. (2010), Zhang and Levinson (2008)
System optimizing model	Nagurney et al. (2010)
Logit assignment model	Chen et al. (2007), Jenelius and Mattsson (2012), Masiero and Maggi (2012)
All-or-nothing model	Lu and Peng (2011), Taylor and Susilawati (2012)
Stochastic Probit-based assignment model	Knoop et al. (2008), Lu and Peng (2011)
Dynamic user equilibrium	Burgholzer et al. (2013), Knoop et al. (2012)
Game theory	Bell et al. (2008), Lou and Zhang (2011), Lownes et al. (2011), Murray-Tuite and Fei (2010), Murray-Tuite and Mahmassani (2004), Perea and Puerto (2013), Ukkusuri and Yushimito (2009)

analyzed separately. Likewise, the relationship between structure vulnerability and functional vulnerability cannot be found (Issacharoff et al. 2008). However, in most of the literature, vulnerability estimation has been conducted using only traffic-related factors and spatial-related factors, irrespective of the topological character of the network itself. Nine traffic assignment models are summarized in Table 5. These studies seem to ignore the relevant topological-related factors. They instead focus on providing a sound traffic assignment model under a disruption scenario.

Any network system, in fact, can be thought of as being intrinsically vulnerable, i.e., its functionality could be significantly reduced due to some failure produced by unexpected events, either internally or externally (Issacharoff et al. 2008). Complex network theory (Barabási and Albert 1999) is widely used in the vulnerability analysis of transportation networks (Angeloudis and Fisk 2006; Berche et al. 2009; Derrible and Kennedy 2010a; Ghosh et al. 2011; Jordán 2008; Qian et al. 2012; Scardoni and Laudanna 2013; Schintler et al. 2007; Takadama et al. 2007; Yin and Xu 2010; Zhang et al. 2011; Zio et al. 2008), where topological-related factors are considered in the estimation of vulnerability. However, considering topologies alone is not enough to reflect the vulnerability of transportation networks accurately. Kurant et al. (2007) and Ghosh et al. (2011) used the number of trains on the link to weigh the link, thus evaluating how vulnerable the railway network is after links or nodes are removed. For both weighted and unweighted topological transportation networks, it has been shown that the more heterogeneous the network, the more vulnerable it is to a targeted attack. This implies that, aside from structural vulnerability, it is necessary to consider the dynamical vulnerability of a transportation network, which is its functional response to a given disruption.

A combination of the topological and functional analysis approach has been applied to highway networks by Issacharoff et al. (2008). Here, a complex network theory based approach was used to estimate the structural vulnerability of highway networks using topological-related factors. A four-step static traffic assignment was used to estimate the functional vulnerability of highway networks by the total travel time increase for all the travelers. The results of the structure and functional vulnerability were found to be similar, with a linear dependence between the magnitude of perturbation and the level of vulnerability. This implies that if a relationship between the topological characteristics and functional vulnerability could be found, it would be easy to assess the functional vulnerability of a transportation network by its structure.

Although the approach proposed by Issacharoff et al. (2008) makes considerable progress in the combination of topological and traffic related factors in vulnerability analysis, it is not capable of reflecting dynamic delay/congestion propagation (Li et al. 2011; Wu et al. 2007). Because of this, a dynamic approach that combines topological and traffic-related factors in the vulnerability analysis is desirable.

Future Directions

Vulnerability Analysis of Multilayer Transportation Network

The infrastructures on which our society depends are interdependent and interconnected across multiple layers. The failure of a very small fraction of nodes in one network may lead to the complete fragmentation of a system of several interdependent networks, due to both functional and physical interdependency. For example, in Italy's electrical blackout on September 28, 2003, the shutdown of power stations led directly to the failure of nodes in the Internet communication network, which in turn caused a further breakdown of power stations (Buldyrev et al. 2010).

Based on complex network theories, many researchers (Albert and Barabási 2002; Barabási and Albert 1999) have focused on the structural vulnerability of interdependent infrastructures (Apostolakis and Lemon 2005; Buldyrev et al. 2010; Chai et al. 2008; Hellström 2007; Little 2002; Matisziw et al. 2009; Ouyang et al. 2009; Rosato et al. 2008; Wang et al. 2012, 2013; Zhang and Peeta 2011). Although all of these focus on multilayer, interdependent infrastructure, most deal with power and Internet networks (Buldyrev et al. 2010), power and gas pipeline networks (Ouyang et al. 2009; Wang et al. 2013), power and water networks (Wang et al. 2012) and power, water, and natural-gas networks (Apostolakis and Lemon 2005). The spread of resources and data flow in power, water, natural gas, and Internet networks is different from passenger flow in transportation networks. The former spread is assigned by the operators, while passengers can choose any available path according to their experience and preference. Therefore, the methods of vulnerability estimation of multilayer interdependent networks such as power, water, natural gas, and Internet networks cannot be applied in multilayer transportation systems.

A relatively simple approach proposed by Johansson and Hassel (2010) is used to estimate the vulnerability of multilayer railway networks. The loss of service is evaluated as the fraction of travelers not able to reach their desired destination. Provided there is at least one possible way to travel between the stations, it is said that no consequences arise. Although this multilayer-based vulnerability approach is designed for multilayer railway networks, which have the same subsystems (electrical in-feed system, auxiliary power system, telecommunication system, and traction power system) as multilayer subway networks, the former is schedule-based, while the latter is frequency-based (Schmöcker et al. 2008). Congestion, a problem not present in railway networks, can be seen in subway networks during peak morning and night hours. It is a daily problem in many developed cities such as London, Tokyo, Shanghai, and Beijing. Therefore, a specific approach is needed for vulnerability estimation of multilayer subway networks, one that considers the frequency of train movements, the strict capacity constraint of stations and trains, congestion in stations and trains, queuing at stations, and delay propagation on rail tracks.

Relationship between Structure Vulnerability with Dynamical Functional Vulnerability

It has been widely observed in many areas that scale free networks are more vulnerable (structure vulnerable) than random networks (Barabási and Albert 1999). Additionally, networks with relatively higher clusters and lower degrees have proven less vulnerable than scale free networks, which have higher clusters and higher degrees (Angeloudis and Fisk 2006; Derrible and Kennedy 2010a). This means that topological characteristics such as degree, cluster, and structure type help to determine the structure vulnerability of the network.

Subway transportation networks have several kinds of structure types. The most typical types are the radial network, dispersed network, grid network, ring-dispersed network, ring-grid network, and ring-radial network (Vuchic 2005). The radial network is the most heterogeneous, as most tracks are connected by very few transfer stations, with most stations only on one track (Derrible and Kennedy 2010b). Therefore, the scale factor is higher than in the other types of structure. The grid network is the most homogeneous network, as many stations are transfer stations passed by two or more tracks. The scale factor is lower than in the radial network. The type of transport network structure used is derived by travel demand, while traffic dynamics are in turn determined by the structure of the transportation networks. The stricter characteristic can be used to explain the formation mechanism of congestion and propagation (Li et al. 2011). Therefore, it would be meaningful and interesting to explore the relationship between both structural vulnerability and characteristics and functional vulnerability.

Dynamic assignments should be considered in functional vulnerability analysis, as they are better at showing the exact location of congestion and at determining the development of congestion over time. This is important for correct modeling of the effects of variations in demand and capacity. The possibility of en-route route choice is important as, in practice, a certain percentage of the travelers will change their route when they are informed of congestion at a specific location. However, it is very difficult to model the en-route choice of travelers correctly because of the uncertainty during such incidents (Knoop et al. 2012). It is not known how many people will have information relating to the incident, nor how they will respond to that information. Static transit assignment models cannot deal with the bottleneck-induced congestion problem and are not able to properly evaluate the transit network under dramatically changing network conditions (e.g., passenger arrival rate and loading of transit services) during the period of analysis (Snelder et al. 2012).

Conclusion

Four common aspects—research objectives, transportation modes, disruption scenarios, and vulnerability indicators—were generalized from the 101 papers selected. Eight objectives of the vulnerability of transportation networks were identified. Road and highway networks were considered in 70% of these papers. Only 3% of approaches were developed for multilayer railway networks and 7% for subway networks. Disruption scenarios are classified by their duration, time of occurrence, induced capacity reduction, simultaneously degraded number of components, and the location of the disruption. Because computational intensiveness is an acknowledged problem in simulation-based vulnerability estimation, many preselected topological and functional indicators are used to overcome it. The vulnerability indicators are classified and analyzed from the impact factors they include, such as spatial-related factors, topological-related factors, and traffic-related factors. The vulnerability indicators most frequently found are traffic-related factor driven, with few including both topological-related and traffic-related factors.

The research findings of this study also offer two future directions. First, more focus on vulnerability analyses of multilayer transportation networks is needed. As more electric transportation systems (subway, light rail, national railway, tram, and electric highway) are provided in cities, there is an increased need for evaluating the vulnerability of transport networks from a multilayer perspective. Second, a new method that can explore the relationship between the structural vulnerability and the functional vulnerability dynamically is needed to assess the functional vulnerability of a transportation network by its structure during the design phrase when the traffic flow is difficult to forecast.

In adopting the four research themes, the general comparison and summary not only provide a general research methodology for transportation vulnerability analysis and the current state of knowledge, but they also identify areas in need of attention while providing researchers with a clear research direction for the future. The analysis provides an avenue to the discovery of new knowledge and an improved understanding of transportation network vulnerability. A better understanding of the recent advances in modeling the vulnerability of transportation networks may enable practitioners to appreciate the key issues of the vulnerability of transportation network development. This will then improve the serviceability of transportation networks in general.

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