https://doi.org/10.3311/PPtr.39859

Periodica Polytechnica Transportation Engineering, 53(3), pp. 292–300, 2025

Sensitivity Parameters of Transport Networks and Vulnerability Assessment of Critical Network Elements

Literature Review

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Received: 14 January 2025, Accepted: 05 April 2025, Published online: 15 April 2025

Abstract

Network sensitivity has recently become an important topic, with an increasing number of articles appearing on the subject. Identification of critical sections within transport networks is also essential for transport modelling. A well-developed methodology can help to improve the network to minimize the impact on road users in the event of future emergency cases (accidents or attacks). For this purpose, existing articles were assessed to determine what progress has been made in network sensitivity and what parameters and approaches have been used so far. After reviewing the articles, it became clear that a significant number of methods have been used to identify critical sections, and it became visible which areas are worth further work. Among the methodologies used, simplified networks have been the main focus, but there is a need for a more detailed analysis based on industry demand and available data.

Keywords

network science, network sensitivity, transportation modelling, transportation, network resilience

1 Introduction

The sensitivity of transport networks has become an important research issue, as knowing this information allows us to plan and avoid negative consequences later on. The study of network sensitivity is also a relevant topic for transport modelling, as is the identification of critical elements of transport networks. We wanted to explore the parameters needed to provide more accurate analyses for the feasibility of transport projects using macroscopic (strategic) traffic models.

Knowing the parameters and methods to identify the critical elements of the network allows us to identify the weak points of any networks. This method is important in the event of random and unexpected accidents. Also, in the case of an intentional attack, it is important to know how traffic will be rearranged and which parts of the city will be difficult to access for traffic. Knowing the weak points can help in future transport planning. Market orders also often raise questions about how a transport network will react in the event of a disaster.

With this aim, we reviewed the articles published so far to summarize the results, methodologies, and observations on the topic. We will then use them to systematize the parameters and methods relevant to traffic modelling and to quantify the vulnerability of critical elements.

2 Review of approaches

The number of publications on the topic of transport-related network sensitivity is very significant, which demonstrates the relevance of the topic. The published literature can be divided into several groups, which could even be classified according to the research objective. However, based on a review of articles from the last 5–10 years, they have been grouped into two main categories. These two groups are given by the way the problem is approached:

1. Network science approach;
2. Non-network science approach.

Following the selection and review of the literature, this grouping seemed appropriate for the topic, as the parameters involved are more similar and there is greater agreement on the network science approach. For this reason, these literatures should be treated as one group; the grouping of parameters in the other articles was not so consistent. It can also be seen from the references that most of

Cite this article as: Gosztola, A., Horváth, B. (2025) "Sensitivity Parameters of Transport Networks and Vulnerability Assessment of Critical Network Elements: Literature Review", Periodica Polytechnica Transportation Engineering, 53(3), pp. 292–300. https://doi.org/10.3311/PPtr.39859

the articles on this topic were published in 2020 and 2021. Several articles mention that this is the year when network science became a hot topic, with a rapid increase in the number of articles in the field. The results so far will be presented in Subsections 2.1 and 2.2.

The papers are grouped into different categories according to the kind of network that was examined in them. Besides this, they are separated into two columns, which is the type of the approach of the problem; Table 1 shows this result.

2.1 Network science approach

In this approach, the publications on network sensitivity can be divided into several parts. The first paper (Wen et al., 2022) developed an assessment method for the vulnerability of logistics networks. For this, three calculations were applied:

- Neighborhood-based centrality: It indicates the position of each node in the network;
- Gravity-based centrality: It takes into account the information of each node and its relationship with other nodes;
- Iterative refinement centrality: It indicates the influence of each node based on the influence of its neighbors, rather than the number of neighbors.

Within logistics, the calculation has been tested on seaports, using normalized values for the three characteristics to determine the importance of the role of different ports. Their results are independent of transport sectors, as the methodology is based on network connectivity.

A review paper also analyses a list of publications on complex networks (Sugishita and Asakura, 2021), from which six conclusions are made, based on the results obtained, and the keywords most frequently used in the references are highlighted. In this 2021 review, one of the main conclusions is that the relationship between complex networks and transport networks is not fully explored. This is supported by the number of articles published on the subject. A similar review of resilience has also been carried out based on recent events (Serdar et al., 2022). A comparison of indicators and methods used in the field of resilience was made.

Table 1 Summary and grouping of the literature reviewed

Field of research	Network science approach	Non-network science approach
Road network	3, 4, 5, 6, 10, 12, 15, 16, 17, 18, 19, 20	23, 26, 27, 29, 30, 31, 32, 34, 35, 36, 38, 41, 43, 45, 46, 47, 48, 49, 50, 52
Aviation	–	25, 28, 51
Rail network	7, 8	51
Independent transport network	2	24, 37, 40, 42, 44
Logistics	1	21, 22
Other network	9, 11, 13, 14	33, 39

Studies have been carried out on road networks in China in relation to intentional attacks (Liu et al., 2020). Node centrality was considered in the calculations and a correlation analysis between the 2-2 parameters was performed. In the paper, it was highlighted that only microscopic factors are emphasized in security analyses. Furthermore, this direction has been followed in other research (Collins et al., 2018).

The following study focused on the evaluation of integrated transport systems within urban agglomerations (Chen and Lu, 2020). Calculations were performed to support the decision, using indicators from previous publications (Liu et al., 2017; Sugishita and Asakura, 2021; Wang et al., 2017; Zhang et al., 2018). All of them also approach the topic of network sensitivity from a graph theory and network science perspective.

Another subfield of transport, public transport, was investigated from a network sensitivity perspective (Auerbach and Kim, 2022). The main factor was the issue of robustness. The most important statement is that it is not suitable to study networks where there are multiple connections between two points. Thus, for transport networks, this characteristic is not appropriate. However, in this paper, a new robustness parameter was developed that can address this problem.

Related to the previous topic, the optimal connectivity of networks can also be investigated (Auerbach and Kim, 2021). However, this is not a straightforward task for existing networks, as the network cannot be completely rebuilt.

Using a Chinese example, the general travel cost model was applied, which is based on vehicle operation, travel time, and travelers' convenience (Leng et al., 2018). Then, the network efficiency index was selected as the vulnerability assessment index: The network efficiency index consists of the traffic volume and the overall travel cost, which are obtained from the equilibrium state of the network. The research also analyzed the impact of traffic capacity reduction, road segment attribute value, and road segment location on vulnerability.

Most of the publications on network science refer to a book and an article by a mathematician (Barabási, 2016; Barabási and Albert, 1999). Albert-László Barabási has been working on network science since the early 2000s and since then his articles and books have been referenced in many articles.

The sensitivity of junctions was studied in another publication (Piraveenan and Saripada, 2023). On the basis of the centrality metrics used in network science, a new metric was introduced that not only considers the shortest path. This was called "All-Path centrality" in the paper.

Another example is in the series of natural disasters (Mahajan and Kim, 2020). Critical elements are searched within the network that need to be upgraded in the future due to the events that occur. Several features are used together to make an assessment, which helps to look at the network and the given situation from several perspectives in road examples. This topic has also been addressed by other writers (Wu et al., 2021).

Similarly, the authors tested their method on a Malaysian road network to determine the impact of potential accidents on sections most vulnerable to traffic rearrangement (Redzuan et al., 2022). Two indices were used:

- Vulnerability index: it is based on the support of alternative routes;
- Aupporting vulnerability: it measures the potential for a road section to become a supporting alternative route.

Simplifications were applied in the calculations; only main roads were considered. Furthermore, a Dijkstra algorithm was used to determine the shortest route and the value of betweenness was calculated.

There was an applied computational method in the previously written literature that did not require major simplifications, but also did not significantly increase the computational demand (Huang et al., 2024; Liu et al., 2024).

The most frequent attributes listed in the literature were node centrality and betweenness. These values were used to define the critical elements of transport networks. All of the listed papers approached the issue from a network science perspective.

2.2 Non-network science approach

In the field of network sensitivity, there are many examples of cases where the approach is not from a network science perspective. These publications also use a variety of indices in their calculations and try to identify the parameters that determine the sensitivity of networks through practical examples.

An evaluation methodology for the vulnerability of logistic networks was developed by Lu et al. (2021). It is important to note that in this paper a mesoscopic approach is presented, calculating the vulnerability of roads based on different characteristics of the infrastructure. In this publication, no connection is made with macroscopic modelling and the network. Logistic networks were also studied in the next published article, where a different proprietary metric was developed for the assessment (Wei et al., 2024).

Another article also included a mesoscopic view, in which two-layered thinking was presented (Sugiura and Chen, 2021). However, there was no feedback between the mesoscopic and macroscopic analyses. Critical and vulnerable intersections were identified in the calculations and minor roads in the network were excluded from the analysis. It highlights the relationship between demand and capacity, as the relationship between these two values makes a big difference in terms of vulnerability.

In the following article, three concepts are compared to each other, to which level the network is characterized and how far each parameter differs from the other (Gu et al., 2020):

- Reliability;
- Vulnerability;
- Resistance.

The result was that the three concepts do not derive directly from each other.

The study of Zhou et al. (2021) uses the example of the Covid epidemic to illustrate the vulnerability of the air transport network. Although it is not a current topic, it is a good example of a case where a sudden disaster or epidemic changes transport patterns and thus disrupts the system. A new method was developed to assess the impact of changes in airport connections and capacity reductions. It is important to note that although network science is not mentioned in the article, details of the methodology is described by Albert-László Barabási (Barabási, 2016) in his book.

A decision support method was developed for natural disasters, which could serve as a good basis for further developments (Ulak et al., 2022). For the calculations, the network elements were also weighted according to "land use" data. These land use data are also important for strategic traffic modelling, as they are used to determine traffic demand and the traffic attractivity of the network areas. Simplifications were also made to the network in the analysis.

The following article aims to improve the resilience of networks to unknown failures (Rahdar et al., 2022). Also, to minimize the total travel time. A three-layer method was defined in which the optimal traffic load is assigned first to the network. Then, the middle level analyses the network in terms of resilience, and then an algorithm is used to determine the subsequent optimal improvements.

Another airport study used four examples to identify the factors that make an airport transport hub vulnerable or resilient (Malandri et al., 2023). The study shows that it is important to characterize the disturbances of the system, not to generalize. Furthermore, the duration of the disruption is important; there is a strong correlation between duration and vulnerability.

One study analyzed an urban road network using existing software (Toma-Danila et al., 2020). The "Networkrisk" module integrated in ArcGIS Desktop was used for the analysis. The module requires a lot of input data and is in development, but can be downloaded for free and used to test any case after the necessary coding. It helps in decision making. Other researchers ranked sections of the network based on existing data and disturbances that had occurred (Ansari Esfeh et al., 2022). Critical sections are often displayed in map form for better interpretability (Engidaw and Terdik, 2024; Taylor and Susilawati, 2012).

The economic costs of road network disturbances were calculated by Kurth et al. (2020). The quantifying of resilience can be interpreted and calculated in several ways, based on several characteristics (Ganin et al., 2017). Furthermore, the evaluation can be done by approaching different important buildings (e.g., a hospital) (Melkote and Daskin, 2001). Economic impacts also encompass accidents, with the consequences of various hazardous situations being equally severe. Numerous articles have been published on methods for calculating these effects (Holló and Sipos, 2020; Ötvös and Török, 2024).

The ability of the transport network to resist traffic was also analyzed using GPS data from taxi rides in New York City. The method used average travel time deviations (Donovan and Work, 2017).

The topic of network resilience is relevant in many areas outside of transport, including supply chain issues and modelling (Heckmann et al., 2015). Network resilience has previously been studied using transport models (Mattsson and Jenelius, 2015). From a modelling point of view, the use of a prediction component improves the accuracy of the models used (He and Liu, 2012). The PAC model has been shown to be suitable for the determination of critical points (Matisziw and Murray, 2009). Further quantification examples are given in several papers where the aim is to analyze resilience and robustness with measurable data (Cui et al., 2024; Zhou et al., 2019).

Bridges and tunnels have been identified as bottleneck sections, and the width of the track has been identified as an important element in the studies (Sventekova et al., 2021; Urbancová and Sventeková, 2019). However, cities and networks with major nodes that are easily accessible and optimally located are less vulnerable to network damage (Buzna et al., 2006; Reggiani, 2022).

Among the published papers, there are several that try to address the problem of capacity in existing networks (Jiang et al., 2022). This also shows that some cases of critical situations would put even more burden on already overloaded networks. Furthermore, anticipating the current situation, they are also looking at the future of network resilience, trying to find a way to incorporate resilience into the development of transport infrastructure (Lee et al., 2022).

Node location optimization has also been addressed to reduce potential losses (Cui et al., 2022). This way of thinking could also be a way forward for the future on this topic. There are several examples of crowded and poorly designed junctions that create issues in transportation (Farooq et al., 2024).

The literature listed in this group shows that a number of approaches have been used to identify critical elements. This is why these two groups were necessary; if we do not consider transport networks from a network science point of view, the attributes that emerge are more different. It is important to emphasize that the traffic and capacity of the section and the ratio of these play a significant role in determining the critical elements. Furthermore, another important factor in addition to this is the number of alternative routes.

3 Comparison: research gap

Table 2 presents a comparison of a smaller selection of the literature that we reviewed, based on the following criteria. Table 2 shows where the topic is located within the transport sector, what events (accidents, failures, attacks, etc.) were analyzed, and what the intentions were.

The following network attributes and their descriptive elements were used to identify critical road elements in an urban environment:

- Node centrality: is a measure used to determine the importance or influence of a node within a network. Various centrality metrics, such as degree centrality, closeness centrality, and betweenness centrality, capture different aspects of importance.
- Section capacity to traffic ratio: it compares the capacity of a road section, representing the maximum

Table 2 Comparison of literatures based on network science and mesoscopic characteristics

References	Transportation types	Methods of attack	Decision support	Network science is mentioned	Mesoscopic approach
Ansari Esfeh et al. (2022)	Independent, for all types of transport	–	–	Yes	–
Kurth et al. (2020)	Road transportation	–	–	–	Yes
Liu et al. (2020)	Independent, for all types of transport	–	–	–	–
Auerbach and Kim (2022)	–	–	–	Yes (complex network)	–
Barabási and Albert (1999)	Road transportation	Direct attack	Yes	Yes	Only micro characteristics are taken into account for safety
Buzna et al. (2006)	Independent, for all types of transport	Multiple attack methods (natural disaster, direct attack, random failures)	Yes	Yes (complex network)	–
Liu et al. (2017)	Aviation	Pandemic	–	–	–
Leng et al. (2018)	–	Critical event	Yes	–	Yes (double layered, but no feedback)
Liu et al. (2024)	Road transportation	Natural disaster	Yes	–	–
Cui et al. (2024)	Public transport	–	Yes	Yes	–
He and Liu (2012)	Road transportation	Natural disaster (forest fires)	Yes	–	–
Holló and Sipos (2020)	Road transportation (just main roads)	Natural disaster, accidents	Yes	–	–
Lu et al. (2021)	Road transportation (just main roads)	Resilience to unstable disturbances	Yes	–	–
Mahajan and Kim (2020)	Aviation	Disruptive events	Yes	–	–
Malandri et al. (2023)	Road transportation	Natural disaster	Yes	–	–

number of vehicles it can handle under ideal conditions, to the current or expected traffic volume. A ratio close to or exceeding 1 indicates congestion as traffic demand approaches or exceeds the roadway capacity.
- Traffic volume: it refers to the number of vehicles that pass a specific point on a roadway during a given time period, typically expressed as vehicles per hour or per day.
- Number of alternative routes between two end points of a closed section: it refers to the total of distinct paths or detours available for traffic to travel between the two points when the primary route is inaccessible. This metric is essential to evaluate the resilience and redundancy of a transportation network.

As can be seen in the brief summary paragraph of the two classifications, in the network science approach, the attributes and network characteristics used to define critical elements are more similar with less variation. This is the explanation of node centrality. In the analyses under the non-network science approach, the attributes used were more divergent, with higher variance. The literature reviewed on this topic was used to determine the volume of traffic and its relationship to capacity, as well as the number of alternative routes between two points on the critical element.

From Table 2, it is clear that microscopic features are mentioned in some articles, but their application is not common, rather macroscopic features are considered. In a few places, it is mentioned that microscopic characteristics also play an important role in the application of

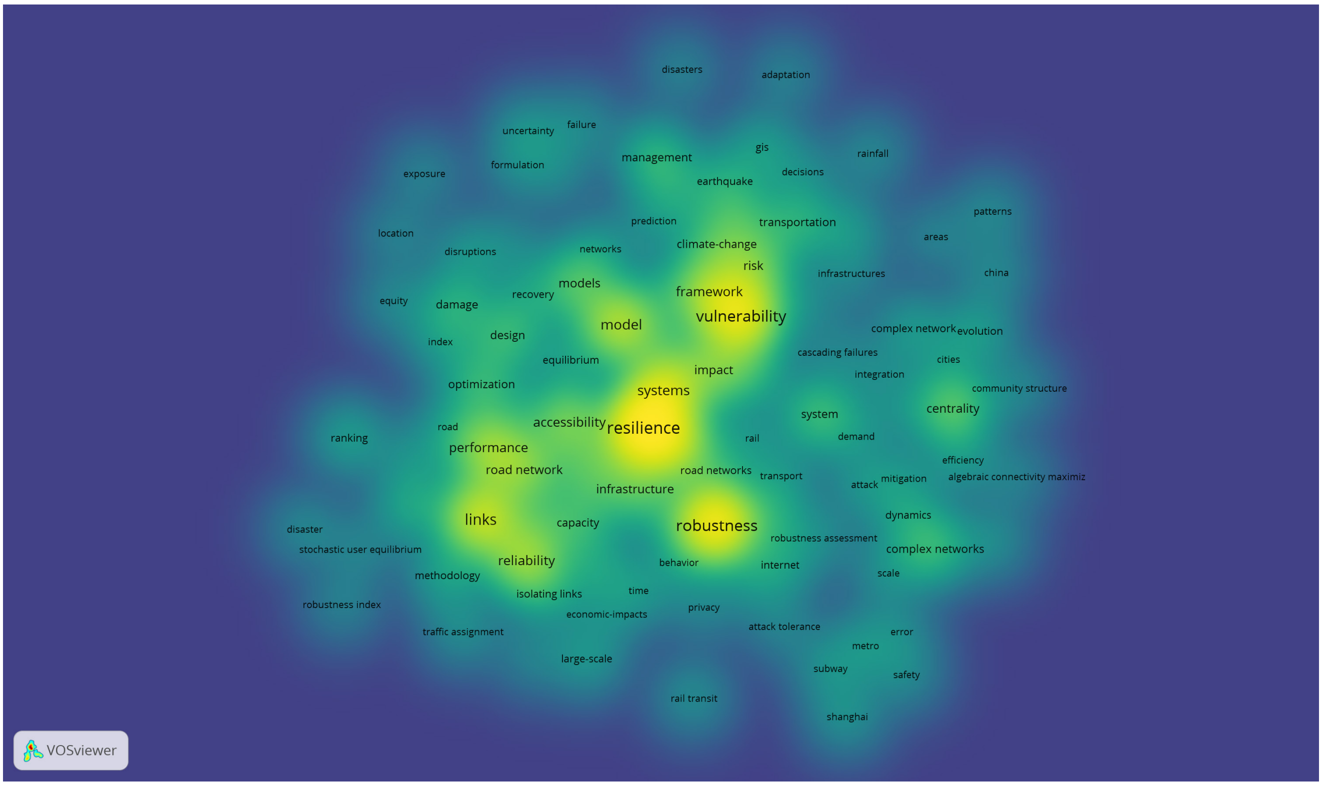

Fig 1 Frequently used words and phrases in the field of network sensitivity

strategic models. These characteristics appear at the level of mention, or the two-level approach is used together, but the feedback between the two levels of modelling is not mentioned in any of the papers.

Among the literature reviewed, several included quantification of the negative impact on the network beyond the definition of critical elements. The extent of delays on the networks, congestion on the networks, and variations in the availability of important locations (e.g., hospital) were mentioned as parameters. Traffic models were used for analysis in several papers.

In addition to the literature published on the topic of network sensitivity, they were aggregated and analyzed using software. Fig 1 shows the most frequently occurring words.

4 Discussion

In all of the articles mentioned above, the vulnerability, resilience and flexibility of transport networks or other networks were examined. In many cases the approach was different, dealing with natural disasters, improving urban transport. However, in most cases the aim was the same, to analyze and assess the network from some point of view, so that the information could be used to plan for the future.

In terms of approaches, published journals can be divided into two distinct groups: some authors sought answers through network science, while the other group developed a methodology for evaluation without it. It can be seen that those who started with network science took similar factors into account in their analysis. However, for those who took a different approach, the factors taken into account differed to a greater extent. From the reviewed literature, it is possible to identify a list of attributes that are more likely to identify critical elements of the urban road network.

Based on the literature reviewed, two important observations can be made:

1. When assessing network sensitivity, it is important to consider microscopic attributes in addition to network detail and macroscopic attributes.
2. Detailed and accurate modelling is required to quantify the impact of a critical element on the network.

The two findings are interrelated. In most of the papers, a network was studied in which simplifications had been made. This is because in urban models the inclusion of all residential streets would be computationally demanding. However, modelling expectations are changing in the opposite direction, where we now often want to know the consequences of every small change and intervention, as industry expectations of models are changing, where they want to know more and more about transport networks through increasingly accurate and detailed modelling methods and algorithms based on complex data models. Accordingly, one needs to take into account, among other things, microscopic characteristics.

Furthermore, it is essential that we can quantify the cost of removal and damage of critical elements in transport networks. For this purpose, strategic transport models have been used in several places to map traffic behavior. This can be used to determine where traffic is being shifted and where congestion is occurring. However, the situations, sudden accidents, closures, etc., discussed in the articles cannot be adequately represented by these models, which are currently in use and can only give approximate results, due, among other things, to the general limitations of the assignment (routing) procedures.

On this basis, it is worthwhile to develop this approach, which has not yet been explored, within the area of network sensitivity, so that the critical elements are not only defined in terms of macroscopic characteristics and the network is not simplified. How can microscopic and macroscopic attributes be taken into account together when assessing the sensitivity of networks? How can the feedback between them be achieved without simplifying the network? Which assignment algorithm can provide a more accurate, direct answer to these questions? Further research is needed to answer these questions. In addition, a modelling methodology is needed to investigate the negative effects caused, so that sudden events can be properly modelled.

5 Conclusion

Based on the literature reviewed, it is worth exploring the topic of network sensitivity further, and based on the engineering and modelling needs, there is a need to analyze detailed networks without simplifications. This requires finding a solution where microscopic and macroscopic attributes can be considered together. Furthermore, it is necessary to find a way to identify the negative impact of the damage to these critical elements on transport networks. For this purpose, a new modelling procedure for strategic traffic models should be developed.

Based on the shown researches the existing assignment procedures are not suitable to handle extreme situations, like critical incidents. Therefore, during the research process, a new assignment method will be developed to manage emergency situations, such as accidents or attacks. This method will be based on several research stages to define the behavioral patterns that drivers follow during their journeys in private cars. The newly modified assignment method will be implemented using the existing PTV Visum software and Python programming.

Acknowledgement

This project has received funding. It was supported by the National Research Development and Innovation Fund and the Ministry of Culture and Innovation of Hungarian Organizations. The project number is 2024-2.1.2.-EKÖP-KDP-2024-00016.

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