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Vulnerability and resilience of transport systems – A discussion of recent research

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ABSTRACT

The transport system is critical to the welfare of modern societies. This article provides an overview of recent research on vulnerability and resilience of transport systems. Definitions of vulnerability and resilience are formulated and discussed together with related concepts. In the increasing and extensive literature of transport vulnerability studies, two distinct traditions are identified. One tradition with roots in graph theory studies the vulnerability of transport networks based on their topological properties. The other tradition also represents the demand and supply side of the transport systems to allow for a more complete assessment of the consequences of disruptions or disasters for the users and society. The merits and drawbacks of the approaches are discussed. The concept of resilience offers a broader socio-technical perspective on the transport system's capacity to maintain or quickly recover its function after a disruption or a disaster. The transport resilience literature is less abundant, especially concerning the post-disaster phases of response and recovery. The research on transport system vulnerability and resilience is now a mature field with a developed methodology and a large amount of research findings with large potential practical usefulness. The authors argue that more cross-disciplinary collaborations between authorities, operators and researchers would be desirable to transform this knowledge into practical strategies to strengthen the resilience of the transport system.

1. Introduction

Our societies are highly dependent on a number of critical infrastructure systems, including electric power, transport, water supply and sewage handling, information and communication, and banking systems. These systems have gradually become increasingly complex and interdependent. For instance, most of them require electric power, access to computer networks and road connectivity. If the supply of any of these services stops or is drastically reduced, the dependent systems will fail or function at a low level of performance. As one example, in the event of a general power outage, the mobile telephone network will also stop functioning after only a few hours when back-up batteries are emptied. To minimise the costs, infrastructure systems are often designed to work close to their capacity with small margins of reserve capacity and little redundancy. This renders them sensitive to various incidents, technical failures, disruptions, extreme weather, natural disasters, antagonistic actions and other threats. This, in addition to the interdependencies between and within the systems, could lead to serious consequences for society, should a critical component or sub-system fail or break down.

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The focus of this paper is on one specific critical infrastructure system – the transport system. The road system, in particular, is fundamental to the functioning of society in developed as well as developing countries. Society is not only dependent on the road system for people's daily mobility and for goods transport, but it also serves as a life-line system for rescuing people and economic values and for repairing and restoring other infrastructure systems when they are disrupted.

The importance of a robust and reliable transport system from an economic and welfare perspective has led to considerable research in order to understand the mechanisms and interrelationships that create its vulnerability, to find ways to make it more robust and resilient, and to mitigate consequences of disturbances and disruptions. The research efforts have accelerated in recent years, the scope has widened and much new knowledge has been added since Berdica (2002) reviewed the road transport vulnerability literature a decade ago. In this article we discuss what has been achieved since then with an emphasis on the most recent contributions, also taking into account other transport systems than roads. The number of studies is too large and dispersed to make a complete review possible. Our aim is instead to select a number of interesting studies and critically describe their methodological approaches, developed tools, research findings and conclusions. By describing the studies in some detail, our hope is that the article will be useful for researchers and practitioners when judging the opportunities and limitations of present research for practical vulnerability and resilience studies.

The rest of the article is organised as follows. The concept of transport vulnerability is discussed in Section 2 and its relationship with resilience in Section 3. Section 4 provides a literature overview of recent transport vulnerability studies with a focus on contributions to the methodology. The overview starts with topological studies of transport networks based on graph theoretical concepts followed by transport system studies, which add behavioural aspects through travel demand and supply models, and ending with a discussion of their respective merits and drawbacks. In Section 5 we discuss the need for viewing vulnerability analysis as part of a broader resilience perspective and add a discussion of some studies on how to improve the response and recovery phases after a disaster. Section 6 concludes the article.

2. Transport system vulnerability

There is no commonly accepted definition of transport system vulnerability. The definition suggested by Berdica (2002, p. 119) is, however, often cited and representative of part of the literature (her emphases): "*Vulnerability* in the road transportation system is a susceptibility to *incidents* that can result in considerable reductions in road network *serviceability*." This definition is equally valid for other modes of transport. It emphasises that there is an initiating disruptive event, that the fundamental purpose of the transport system is hurt (its ability to provide transport services to the users), and that the adverse consequences are significant. A somewhat shorter formulation with essentially the same meaning is: "Transport system vulnerability is ... society's risk of transport system disruptions and degradations" (Jenelius and Mattsson, 2015, p. 137). Risk is here perceived in accordance with Kaplan and Garrick (1981, p. 409), who suggest that a risk analysis should answer the questions: "What can happen? How likely is that? What are the consequences?" For every conceivable risk scenario this can be formalised as a "triplet": a scenario description, the probability and the consequences (measure of damage) of that scenario, respectively. Risk is then conceptualised as the set of all possible such triplets. This is a fundamentally richer description of risk than the not uncommon operationalisation of risk as expected consequence: the product of probability and consequence.[1]

The risk concept may be illustrated in the form of a risk curve (see Fig. 1). The scenarios on the horizontal axis are sorted according to increasing severity of the consequence x. The vertical axis indicates the cumulative probability of scenarios with consequences greater than or equal to x during some period of time. There is some controversy about the meaning of probability. Does it represent the (objective) numerical value to which the relative frequency of a specific scenario will tend in repeated experiments or does it represent somebody's (subjective) degree of (un)certainty about the relative frequency of that scenario? Following Kaplan and Garrick (1981) the risk curve could be consistent with both interpretations by viewing it as the expected frequency.

Fig. 1 also illustrates the distinction between (un)reliability and vulnerability. Although we think that it is meaningful and useful to make this distinction, it should be remembered that it is not possible to draw a precise boundary between these concepts. Vulnerability, as we understand it, is about events that are infrequent and have considerable adverse consequences. It is thus related to the lower right section of the risk curve.

Reliability is often used in risk analysis in a well-specified meaning as "the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered" (e.g., in Billington and Allan, 1992). In the transport literature, reliability is used more generally to describe the stability, certainty and predictability of travel conditions. Taylor (2013) and Rasouli and Timmermanns (2014) provide thorough reviews of recent research on travel time (un)reliability and how uncertainty affects travel behaviour. The focus is on the daily variability in travel times and how the traveller by having general (historical) or up-dated (on the route) information on travel time variation can minimise the disutility related to this unreliability and uncertainty.[2] This means that transport unreliability in this sense is related to the upper left section of the risk curve in Fig. 1.

[1] For a recent critical review on supply chain risk, see Heckmann et al. (2015).
[2] See Cats and Jenelius (2014) for an example of mitigation effects of information in public transport.

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